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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD ADVISORY REPORT 329

3-D Surface Anthropometry: Review of Technologies

(l'Anthropométrie de surface en trois dimensions: examen des technologies)

This Advisory Report was prepared by Working Group 20 of the Aerospace Medical Panel of AGARD.

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Editors:

K.M. Robinette (US), M.W. Vannier (US), M. Rioux (CA), P.R.M. Jones (UK)

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North Atlantic Treaty Organization
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3-D Surface Anthropometry: Review of Technologies

(AGARD AR-329)

Executive Summary

The seven chapters in this document describe the dramatic changes taking place in the field of anthropometry due to advances in 3-D imaging technology.

Chapter I lists some of the advantages of 3-D anthropometric techniques, and explains how 3-D technology can overcome many of the limitations of traditional anthropometry.

Chapter II discusses the various fields of 3-D anthropometry applications along with the common technologies used in each field. The emphasis of this chapter is on applications within the medical field, human systems engineering, and clothing technology. An overview of applications within the fields of comparative morphology and virtual reality is also given.

Chapter III describes the various measurement technologies currently available for 3-D anthropometry. Technologies discussed include photogrammetry, videography, surface scanning (lasers and contact devices), and volume scanning. Descriptions of each methodology are discussed along with the significant advantages and disadvantages of each method.

Chapter IV discusses the techniques and technologies used to visualize, model, and analyze 3-D anthropometric data. The discussion covers a wide range of topics, including hardware platforms, software systems, and user requirements applicable to 3-D anthropometric data visualization, modeling, and analysis. This chapter serves to highlight the potential advantages from improving the analyst's ability to visualize, retrieve, and analyze 3-D anthropometric data through the use of state-of-the-art computer technology.

Chapter V is a comprehensive overview of current database and data communications technologies applicable to 3-D anthropometry. Generic and specific design requirements for a 3-D anthropometry data base are discussed. Data communications technologies are also discussed with emphasis on the current networking technologies, communication mediums, and data formats. An extensive discussion on Picture Archiving and Communications Systems (PACS) is also presented, as PACS may become the standard for transferring certain data formats applicable to 3-D anthropometry.

Chapter VI focuses on the emerging technologies and concepts in improving the user interface between software systems and the operator. The technologies and concepts described in this chapter, directly applicable to 3-D anthropometric software systems, are also essentially applicable to all software systems. This chapter describes the basic requirements for the user interface along with application-specific requirements.

Chapter VII closes this publication by highlighting the importance of adopting standards for the wide range of technologies used in the field of 3-D anthropometry. The focus of this chapter is on the 3-D anthropometric data generated from the new technologies used. Major issues discussed include data formats, data storage, and exchanging data between multiple users.

L'anthropométrie de surface en trois dimensions: examen des technologies

(AGARD AR-329)

Synthèse

Les sept chapitres de ce document traitent des récents changements spectaculaires qui se produisent dans le domaine de l'anthropométrie à l'heure actuelle, grâce aux avancées des technologies d'imagerie en trois dimensions.

Le chapitre I évoque certains avantages des techniques anthropométriques en trois dimensions et montre comment les technologies tridimensionnelles permettent de surmonter bon nombre des limitations de l'anthropométrie traditionnelle.

Le chapitre II examine les différents types d'applications, ainsi que les technologies communément utilisées dans chaque domaine. L'accent est mis sur les applications en ce qui concerne la médecine, les systèmes humains et les technologies de l'industrie du vêtement. Le chapitre comprend également un aperçu des applications dans le domaine de la morphologie comparative et de la réalité virtuelle.

Le chapitre III décrit les différentes technologies de mesure actuellement proposées pour l'anthropométrie tridimensionnelle. Les technologies considérées comprennent, entre autres, la photogrammétrie, la vidéographie, le balayage de la surface et le balayage en volume (lasers et dispositifs de contact). Chacune des méthodologies est décrite avec les principaux avantages et inconvénients.

Le chapitre IV présente les techniques et les technologies mises en œuvre pour visualiser, modéliser et analyser en trois dimensions les données anthropomorphiques. La discussion couvre un large éventail de sujets, y compris les plates-formes matérielles, les systèmes logiciels, et les besoins des utilisateurs applicables à la visualisation, la modélisation et l'analyse des données anthropomorphiques tridimensionnelles. Ce chapitre fait ressortir les avantages qui découlent de l'amélioration de la visualisation, de la saisie et de l'analyse des données anthropomorphiques tridimensionnelles dont bénéficie l'analyste, grâce aux toutes dernières technologies informatiques.

Le chapitre V présente un tour d'horizon très complet des technologies des bases de données et de transmission de données applicables à l'anthropométrie tridimensionnelle. Les critères de conception génériques et spécifiques d'une base de données d'anthropométrie tridimensionnelle sont examinées. Les technologies de la transmission des données sont abordées également, l'accent étant mis sur les technologies actuelles en matière de réseautique, moyens de communication, et formats de données. Une étude détaillée des systèmes d'archivage et transmission d'images PACS est présentée, le PACS étant probablement la référence future en matière de transfert de certains formats de données applicables à l'anthropométrie tridimensionnelle.

Le chapitre VI est axé sur les technologies et les concepts naissants pour l'amélioration de l'interface utilisateur entre les systèmes logiciels et l'opérateur. Les technologies et les concepts décrits dans ce chapitre, qui sont directement applicables aux systèmes logiciels anthropométriques tridimensionnels, sont en principe applicables à l'ensemble des systèmes logiciels. Ce chapitre présente la spécification technique de base de l'interface utilisateur, ainsi que les besoins spécifiques aux applications.

Le chapitre VII clôt cette publication en soulignant l'importance de l'adoption de normes communes en raison du champ très vaste des technologies mises en œuvre dans le domaine de l'anthropométrie tridimensionnelle. Ce chapitre porte essentiellement sur les données anthropométriques tridimensionnelles générées par les nouvelles technologies employées. Parmi les thèmes principaux figurent les formats de données, l'archivage des données, et les échanges de données entre plusieurs utilisateurs.

Contents

Preface

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CHAPTER I

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INTRODUCTION

Imagine yourself walking into a virtual store without leaving your living room. You select a garment and try it on a virtual duplicate of yourself (you view it as if it is on someone else) to see how you would look. You can even make your duplicate walk and move just like you do, and you can see the looseness or tightness of the fabric. You can change the fabric on the double in terms of material, pattern, or color. You can change your accessories to see how it would look with previous purchases. You can also alter the garment to get the look or shape you want. When you are finished you place your order electronically and receive a "custom-fitted" garment in the mail a few days later.

While this story may sound futuristic, many of the technologies necessary to make it a reality have already been developed. One of these is three-dimensional (3-D) surface anthropometry.

Anthropometry is the study and technique of human body measurement. Three-dimensional (3-D) surface anthropometry extends the study of the human body to 3-D geometry and morphology of external body tissues. It includes the acquisition, indexing, transmission, archiving, retrieval and analysis of body surfaces and their variability.

New technological advances both in 3-D surface digitization and other areas such as computer graphics technology, automated manufacturing, and electronic communications, are radically changing the field of anthropometry. This book attempts to capture the new technology environment and illustrate the changes and their impact.

Background

Traditional anthropometric data are collected using homologous body surface points (e.g., anatomical landmarks common to all humans, regardless of age or race) and simple measures such as circumferences, breadths, and heights from individuals and populations.

In the early 1970s the U.S. Air Force began to assemble a repository of traditional anthropometric data from both military and civilian surveys conducted around the world. It was originally called the Aerospace Medical Research Laboratory (AMRL) Anthropometric Data Bank. Initially, the repository was a collection of magnetic tapes in a "standardized" format (Churchill et al., 1977). These tapes were utilized as a source for military standards and handbooks, for ergonomics texts (Roebuck et al., 1975), and by the National Aeronautics and Space Administration (NASA) to create a source book containing lists of selected summary statistics and measurement descriptions (Webb Associates, 1978). A similar data repository called Ergodata was created in France at the Universite Rene Decartes in Paris (Coblentz et al., 1986). These magnetic tapes were replaced with on-line networked computer versions of the data repositories in the 1990s (Coblentz et al., 1992, Robinson et al., 1992).

Tables 1-1 and 1-2 are lists of selected traditional surveys of 500 or more adults from this century. These lists are not exhaustive, but are intended to illustrate the prevalence and widely recognized need for anthropometric data. One of the listed surveys is from a previous, AGARD-sponsored, anthropometric survey of selected North Atlantic Treaty Organization (NATO) countries (Hertzberg, 1963).

The amount of traditional anthropometric data collected in this century is due in part to the wide variety of applications for which such data are used. These include: clothing and equipment systems, automobiles and work spaces, occupational safety and health, human growth and development, and the interoperability of shared products between countries, such as U.S. automobiles for Japan. Advances in 3-D surface anthropometry and other related technologies extends the number of applications to reconstructive and cosmetic

TABLE 1-1
Selected Anthropometric Surveys-Adult Males

Population	Year Conducted	Location(s)	Reference(s)
Air Force Flyers	1950	U.S.A.	Hertzberg et al. 1954
Army Aviators	1959	U.S.A.	White 1961
Military Personnel	1959-60	Italy, Turkey, Greece	Hertzberg et al. 1960
Air Traffic Controllers	1960-61	U.S.A.	Snow and Snyder 1965
Civilians	1962	U.S.A.	Stoudt et al. 1965
Military Personnel	1963	Vietnam	White 1964
Navy Aviators	1964	U.S.A.	Gifford et al. 1965
Military	1965	Korea	Hart et al 1967
Air Force Personnel	1965	U.S.A.	Kennedy 1986
Army Personnel	1966	U.S.A.	White and Churchill 1966
Air Force Aviators	1967	U.S.A.	Kennedy 198
Air Force Personnel	1968	West Germany	Grunhofer and Kroh 1975
Military Personnel	1965-70	Several Latin American Countries	Dobbins and Kindick 1972
Military	1970-71	West Germany	Jurgens et al. 1972
Army Aviators	1970	U.S.A.	Churchill et al. 1971
Air Force Aircrew	1970-71	United Kingdom	Bolton et al. 1973
Air Force	1971	Japan	Yokohori 1972
Military	1973	France	Anonymous 1973
Army Personnel	1972-75	United Kingdom	Gooderson 1982
Law Enforcement Officers	1973-74	U.S.A.	Martin 1975
Military Personnel	1974	Canada	McCann et al. 1975
Civilian	1974	Japan	Yanagisawa 1974
Transport Corpsmen	1976	United Kingdom	Gooderson 1982
Military Aircrew	1985	Canada	Stewart 1985
Military	1985	The Netherlands	Brekelmans et al. 1986
Army Personnel	1988	U.S.A.	Gordon et al. 1989
Navy Personnel	1986-90	United Kingdom	Hooper et al. 1991
Military Personnel	1990-91	France	Ignazi 1992
Civilians	1992	United Kingdom	Jones et al. 1993

TABLE 1-2
Selected Anthropometric Surveys-Adult Females

Population	Year Conducted	Location(s)	Reference(s)
Civilians	1940	U.S.A.	O'Brien and Shelton 1941
Army Pilots Air Force Nurses	1942	U.S.A.	Randall et al. 1946
Army Separatees	1946	U.S.A.	Randall and Munro 1949
Civilians	1951	The Netherlands	Sittig and Freudenthal 1951
Civilians	1951	United Kingdom	Kemsley 1957
Civilians	1962	U.S.A.	Stoudt et al. 1965
Air Force Personnel	1968	U.S.A.	Clauser et al. 1970
Civilians	1974	Japan	Yanagisawa 1974
Army Personnel	1977	U.S.A.	Churchill et al. 1977
Army Personnel	1988	U.S.A.	Gordon et al. 1989
Navy Personnel	1988	U.S.A.	Mellian et al. 1990
Civilians	1992	United Kingdom	Jones et al. 1993

surgery, wound healing research, customized equipment and clothing production, virtual reality, and automated manufacturing. Furthermore, by providing a better means for producing solid models and computer engineered prototypes, 3-D surface anthropometry can reduce production time and cost, while at the same time improving fit and performance of products as well as their integration with other products.

Chapter II provides a comprehensive overview of the applications where anthropometry and 3-D surface and volumetric digitizing technologies are being used to image and model the human form and motion.

Three-dimensional anthropometric data have been collected since at least the 1970s. These data can be classified as two types:
1) measurement of a finite set of homologous points (anatomical landmarks) either statically or during motion, and
2) detailed surface measurement on static bodies.
The first type of measurement requires a clear prior definition of all the measured homologous points, referred to as landmarks. On static objects these points were often measured mechanically or by moving a stylus to each of the pre-defined (and often manually pre-marked) points to record the stylus position. For example, Snyder et al. (1972) used moveable scales and plumb bobs to record points on cadavers. Reynolds and Leung (1983) implanted targets in unembalmed cadavers which were then visualized by x-rays in stereo pairs. Gordon et al. (1988) used a mechanical stylus with a computerized 3-D locator for the head measurement of living U.S. Army personnel. A head box with a special clamp was used to move from point to point.

For objects in motion, a small number of landmarks are recorded at multiple time increments as the subject changes position. The points are marked prior to data collection with special reflective markers for photographic or video tracking systems (Nixon and Cater, 1982; Probe, 1990) or with sound emitters for sonic tracking. These are then located in 3-D using camera pairs for the optical methods or microphone arrays for the sonic methods.

Detailed 3-D surface measurement was limited to methods which did not automatically translate to geometric information but rather the geometry had to be somehow manually extracted and recorded. One such method is stereophotogrammetry (Hertzberg et al., 1957, Herron, 1972, Coblentz et al., 1976). Basically, Stereophotogrammetry captures an exterior surface with linked pairs of photographs. While it acquires the images rapidly, the manual digitizing of points in the images is extremely slow and tedious. As a result, the number of subjects digitized in any one study is small; for example, one set of studies which used stereophotogrammetry for estimating mass distribution properties of body segments measured just 31 men (McConville et al., 1980) and 46 women (Young et al., 1983). Figure 1-1 below is a plot of a data set from this study. The detail of the points gives an indication of the gross body form but is not sufficient to identify facial features or distinguish fingers.

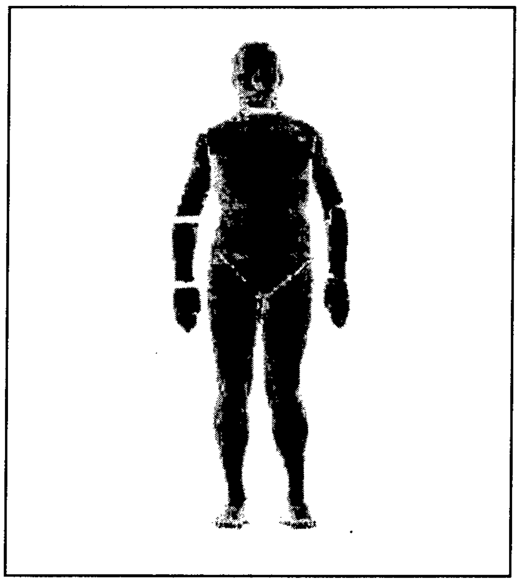

Figure 1-1. A plot of a stereophotometric data set.

In the 1970s, another detailed 3-D method involved 3-D reconstruction either from photographs or x-rays or contiguous tissue slices. In this case the relative locations of slices are recorded and with the earliest

methods the geometric information within a slice is measured manually off the film. This advanced to computerized reconstruction of slices (Katz & Levinthal, 1972, Cahan & Trombka, 1975, Veen & Peachy, 1977), but the reconstructions were still far from being considered automated. This is examined in detail in Chapter IV.

For internal structures 3-D reconstruction was greatly assisted by the invention of ultrasound imaging, x-ray, computed tomography (CT) scanning and magnetic resonance imaging (MRI) which capture the images in slices or volumes. For external details of the human body surfaces, new automated digital scanning technologies began appearing in the 1980s (Altschuler et al., 1981; Arridge et al., 1985; Deason & Ward, 1989; and Jones et al., 1989).

Chapters III and IV examine the more rudimentary steps of data collection, and the methods used to present the data to the user. Chapter III presents the various measurement technologies currently available for 3-D anthropometry. Technologies discussed include photogrammetry, videography, surface scanning (lasers and contact devices), and volume scanning. Descriptions of each methodology are discussed along with the significant advantages and disadvantages of each method.

ADVANTAGES OF 3-D SURFACE ANTHROPOMETRY

Because traditional anthropometry is centuries old, well-established, abundant, easily collected, and readily available (in centralized repositories or elsewhere), it is safe to assume that it will never be rendered obsolete. There are, however, problems inherent with the use of traditional anthropometry; problems that 3-D surface anthropometry resolves and problems which make 3-D surface anthropometry essential for some applications.

The first limitation is that a very large number of ambiguous contours may be derived from the traditional measurements. Therefore, items produced by different manufacturers meeting the same anthropometric specifications may result in products which are very different in terms of shape, and ultimately, fit. In other words, due to this non-uniqueness of the contours, most of the surface of human models in the past were filled in by artistic interpretation. This is true for ergonomic models such as ComBiMan (Bapu et al., 1983), Crew Chief, Mannequin, Sammie, and Jack; Biodynamic models such as ADAM, and VIP; clothing body forms; oxygen mask face forms and head forms for helmets (Ziegen et al., 1960).

The second limitation is that many traditional measurements are dependent entirely upon the orientation of the body segment. Measurements like "tragion to top of head" define the "top of head" as the highest vertical point with the head in the "Frankfort plane" (Ranke 1884) orientation. The Frankfort plane on living subjects is defined in the ASCC AIR STANDARD 61/83 as "... a standard plane for orientation of the head. It is established by a line passing through the right tragion (the front of the ear) and the lowest point of the right eye socket." Figure 1-2 illustrates the problem using two subjects aligned in the Frankfort Plane. In this figure the same two subjects are shown aligned using the Frankfort Plane alignment at the left and as the helmet is actually worn at the right. As can be seen the "top of head" as defined by the Frankfort Plane does not coincide with the top of the head in the helmet for these two subjects. In fact, further investigation reveals that the location of the head in the helmet appears to be dependent upon the contour of the cranium.

This finding means that designers who used traditional measurements for head and face equipment had an unknown and unanticipated error in their points of reference, that of axis system error. This error can apparently be quite large. The error due to misalignment shown in Figure 1-2 constitutes several centimeters with just two subjects.

Designers had little or no surface information and no way of detecting the error. Therefore, in their efforts to design equipment to fit populations, the traditional measurements would lead them to make at least two design mistakes. First, they would create too many sizes because the added alignment error would indicate that the population was more varied than it really was. Second, many of the sizes

wouldn't actually fit anyone very well because the added error would cause them to misproportion them.

It is not surprising therefore that in a test of the HGU-53/P helmet it was found that only two of the six sizes seem to be required, one for men and one for women. The size intended to be the largest, size 6, was improperly proportioned so that in effect, even though larger in volume than the size 5, it does not fit larger heads.

Another, perhaps broader view of this same limitation is coordinate system (or reference frame) dependence. Even summarization and comparison of human shapes based upon three-dimensional landmarks can be misleading if the analysis fails to remove dependency on the position in which the subject was measured. This is especially true since measurement systems typically report results in a coordinate reference system independent of the individual being assessed. This makes the measurement sensitive to one's location relative to the sensor reference frame. This dependency has been termed "observer inherence." Cheverud et al. (1983) and Lele & Richtsmeier (1991) devised methods to make comparisons between subjects using 3-D landmarks. These methods resolve the observer inherence for landmark type data sets for certain types of studies such as comparisons of species of primates, and growth studies, but can be insufficient for applications in which contours and contour changes are critical variables.

With 3-D scanning capabilities, body posture or body segment orientation during the scan is not always critical. This allows the user to select an axis system according to his or her interest, or by the axis system's applicability to a particular problem or circumstance.

Recent studies of helmets (Blackwell et al., 1993, Robinette & Whitestone, 1994) have indicated that information about the true 3-D alignment/location of a person within equipment and clothing can be critical. In other words, it is not enough to know how they might be aligned given their size and shape. It is important to be able to measure how they *are* aligned. For example, in the 1993 fit test of helmets with Night Vision Goggles (Blackwell et al., 1993), some of the subjects could not get both left and right sides of the optics to simultaneously adjust correctly. This indicates an asymmetry problem. However, no significant asymmetry could be detected in the

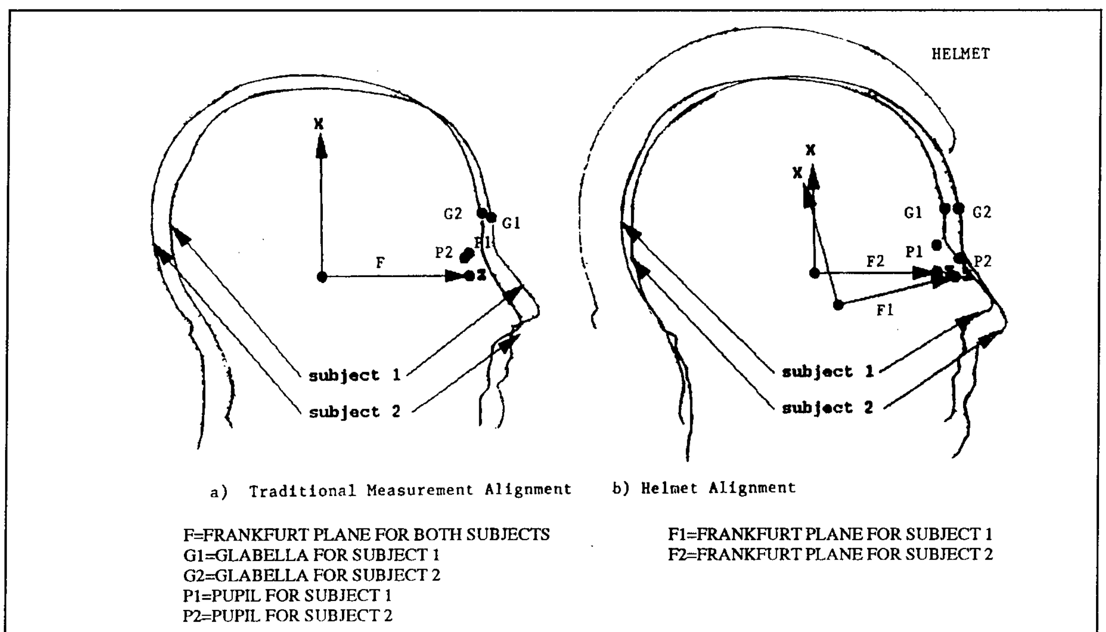

Figure 1-2. Two subjects aligned according to the Frankfort Plane

subjects. Review of scans of subjects within helmets revealed that human asymmetry is not a pre-requisite for asymmetry within a helmet. The cause of the asymmetry problem could easily have been that the helmet was too short from front to back so the subject had to turn it to get a comfortable fit. This type of problem is not detectable with traditional tools.

This brings up a third limitation to traditional anthropometry: its inability to measure the spatial relationship between the person and the equipment or clothing worn. Traditional anthropometry is dependent upon landmarks, many of which become obscured when the equipment is donned. Scanning methods permit the scanning before and after donning equipment and, for at least some items, such as helmets, there is enough body surface area visible in both scans to align the pre- and post-donning scans. This permits viewing of points underneath equipment which would otherwise have been obscured. An example of two such scans is shown below in Figure 1-3.

Figure 1-3. Plot of two scans of one subject.

This is an example of a pilot wearing a size 3 HGU-53/P helmet. This was taken from a 1994 survey of U.S. Air Force aircrew.

By defining head location with respect to the helmet, the axis system can be either anatomically or equipment-based. The flexibility in assigning the axis system also facilitates the creation of "feature envelopes", such as, ear, pupil, nose or chin spatial distributions within a helmet. This can tell a designer where these key points are likely to be for designing components to fit on the helmet. This would mean that they would also know how much adjustment will be necessary for the optics to surmount the asymmetry problem described above.

A fourth limitation of traditional anthropometry is that, with traditional anthropometry there can be large differences in measurement values and techniques between observers who collect the data even if they use the same measurement protocol, and even if the dimensions are described carefully and completely. Beginning with the work of Todd in 1925, many researchers have documented large differences in the way a single person takes measurements from one point in time to another. This source of variability with traditional measurement methods has made it difficult to draw group inferences from different samples because measurements are confounded with intra- and inter-observer variation (Cameron, 1984).

One part of the observer variation has been due to differences in "touch". One investigator may pull the tape tighter than another, for example. Snyder et al. (1977) attempted to create traditional type tools which both measured and standardized the touch forces of the instruments. This was moderately successful for some measures, but the types of measures which could be taken with these tools were very limited. 3-D scanning with optical systems removes this source of variability because it requires no physical contact with the body.

Another part of the observer variation is landmark location interpretation. With traditional data, the original landmark location is the only available choice once the subject departs. With 3-D technology, it is possible to evaluate and adjust the location at a later time. In other words, it is possible to redefine and standardize the location of the landmark at a later date.

Recently researchers have compared 3-D whole body scanning measurements with anthropometric measurements and examined intra- and inter-observer differences of both techniques. In a study using the Loughborough Anthropometric Shadow Scanner (LASS), researchers found that intra-observer differences for the 3-D data were less than the differences

for the traditional anthropometric measurements (Brooke-Wavell et al., 1994). Inter-observer differences for both techniques were very similar. The researchers also found that repeatability of measurements taken from scan data was no greater than the repeatability of measurements taken with traditional tools. They concluded, however, that the scan data is more useful overall because it provides information on shape, volume, and area.

In summary, advances in 3-D scanning technology may allow the user/designer to overcome the limitations of traditional anthropometry. Where the use of traditional anthropometry is limited by its large number of ambiguous contours, the shape information included in 3-D anthropometry alleviates that ambiguity. Where traditional anthropometry is limited to the orientation selected at the time of data collection, 3-D scanning data sets are complete enough that they can be reoriented into many different axis systems long after the subjects are gone. Where the use of traditional anthropometry was limited because the data failed to capture the equipment relationship interface, 3-D anthropometry captures and preserves it. 3-D technology also reduces the observer error found in traditional anthropometry because it removes the effect of touch and because it permits the standardization of landmarks at a later point in time.

IMPACT OF ADVANCES IN OTHER TECHNOLOGIES

In addition to an overall need for 3-D anthropometric data to support a wide variety of application areas, there also exists a need to provide potential users access to the data once it has been collected. Data accessibility covers a wide range of issues dealing with more than just physical extraction or communication of the data to multiple users. It includes the ability to use the data to accomplish one's objectives once the data have been collected. This requires that the data be presented to the user in an intuitive form, that the data may be interrogated to extract the information pertinent to the problem at hand, that analysis tool and models be created to allow interactive analysis of the data relative to specific objectives, and to ensure the data are compatible with the hardware and software systems of multiple users.

Fortunately, new data base technologies, advanced computer graphics, advanced modeling and analysis methods and electronic communication technologies are making it easier to make the data available to the designer, engineer, physician or other user of the data.

User Interface

With the computer becoming a prominent tool used in the collection, visualization, and analysis of 3-D anthropometric data, the interface between the operator and the computer becomes highly significant. A computer system's utility is only as good as the operator's ability to effectively interact with the system to achieve the desired results. Therefore, care must be taken to ensure the user interface promotes the computer as a productive tool and not a source of frustration for the operator. Chapter VI examines the computer system-user interface issue, particularly the software interface, for applications like 3-D anthropometry which are characterized by demanding graphics and visualization requirements. An overview of the evolution of software user interfaces is provided, culminating in the current state-of-the-art methods and approaches used in the design of the software user interface.

Data Communications

Real time communication, or sharing, of 3-D anthropometric data between multiple organizations is becoming a reality with current and new technologies on the horizon. Eventually, users will have on-line access to data within their own organizations as well as other organizations external to their own. This is already being achieved with workstations integrated into a communications network. Users are networked internally within their own organizations via local area networks (LANs) and to external organizations through dial-up access or through the Internet. With the migration to multi-media MMDIR structures and with the emergence of new communications technology, new types of communication channels are being realized. These new

channels will augment traditional communication paths or allow for new methods of imaging interaction between multiple users. Digital imaging workstations may eventually become part of different types of communication infrastructures such as Picture Archiving and Communications Systems (PACS), Information Management and Communications Systems (IMACS), and Telemedicine. Chapter V explores the current communications technology available as well as the new technologies on the horizon for linking individual workstations into a distributed information management system.

Data Base Systems

The most common method for providing data is in the form of printed publications such as handbooks, textbooks, and standards. Unfortunately, published data have very limited utility. Summary statistics which are easy to publish, such as means, standard deviations, and percentiles, are inappropriate for design. This was alluded to by Gilbert Daniels (1952) in his report "The Average Man" and was explained further by many others including Searle and Haslegrave (1969), Bittner (1975), Robinette and McConville (1982), Hendy (1990), Meindl et al. (1993) and Zehner et al. (1994). Digital data bases have been created, such as those mentioned earlier, but most of these are essentially computerized versions of the published documents which do not provide full access to the original data. Even when statistical capabilities are available, they are limited; the user of the data base generally needs extensive knowledge of the particular computer system, of the statistical software and of anthropometry in general, if he or she is to effectively use the information.

The success of a distributed information management system will hinge a great deal on how the data itself is structured, stored, accessed, interrogated, formatted, etc. Historically, on-line access to 3-D anthropometry data has emphasized data storage with little emphasis on data management and analysis. This approach is expectedly not very efficient for sharing information, or for storing complex data sets. Molenbroek (1994) very eloquently describes and demonstrates the need for interactive data systems that allow access to complete data sets for re-analysis as needed.

In addition to the 3-D anthropometric image data, there are also many other associated types of data which must be accessible. Demographic and human system integration data are just two examples. An example of human system integration data would be fit-test results for a helmet system, and the digital head and helmet geometries associated with the fit. Fit data entities include variables such as comfort rating, a center-of-gravity location, a stability measure, or, as illustrated in Figure 1-4, an image which identifies regions that are uncomfortable.

For medical imaging applications, demographic information and related patient records (usually in text or graphic format) are needed in addition to the image data. Each of these are data entities that must be accessible along with the 3-D anthropometry image information. For a particular patient or subject, the sum total of the collective information may be labeled the multi-media digital imaging record (MMDIR), particularly if sound and/or video sequences are included.

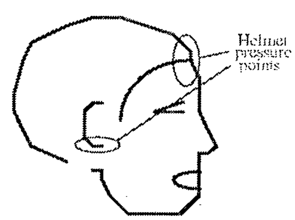

Figure 1-4. Example of a helmet "hot-spot" notation.

What is needed is a data management system that has the ability to share information between multiple users and to store and interrogate complex sets of data. Chapter V also discusses the issues of providing an information or data base management system (DBMS) for managing 3-D anthropometric data. This chapter will describe the various data base system technologies available and identify the basic characteristics desired for a 3-D anthropometric DBMS. A brief history of data base development is also provided for the reader's edification.

Automated Manufacturing and Prototyping

New manufacturing technologies are making it possible to: 1) produce prototypes quickly to test design concepts, 2) create customized equipment for individuals, and 3) produce the final products faster and therefore cheaper than ever before. In the clothing industry there are computer-controlled cutting systems for cutting out the clothing pieces from a computerized pattern. For personal equipment such as footwear or helmets there are tools such as numerically-controlled milling or stereolithography to produce foot lasts or helmet molds from the 3-D computer drawings. For these new technologies to work best they require 3-D representations at some stage. 3-D surface anthropometry can provide the 3-D human models much more quickly and accurately than traditional anthropometry.

3-D ANTHROPOMETRIC DATA REQUIREMENTS

The basic need for 3-D anthropometric data is easily demonstrated in the fact that there currently exists an insufficient international data pool of 3-D surface anthropometry to permit identification of and adjustment for differences in ethnic composition among the populations of participating AGARD member nations. A representative international data pool would provide the ability to establish design criteria specific to a given nation, as well as options for equipment interchangeability among participating nations. Jurgens et al. (1990) recognized the value of such data pools for the purpose of "international harmonization of consumer goods and workspace design" in their report of comparative anthropometry.

An example of the magnitude of these ethnic and population differences is provided by the previous study of NATO countries by AGARD (Hertzberg et al., 1963). This collection includes data from three countries gathered by the *same* observers. The use of the same observers should remove the effect of differences due to measurement techniques or style thereby providing better estimates of differences in the anthropometry of the populations. The means, standard deviations, and sample sizes for stature and mass (weight) are shown in Table 1-3, along with an indication of the statistical significance of the differences in the means. The mean stature of the Turkish population is significantly different from the stature of both the Greek and Italian populations. The mean statures from the other two countries are not significantly different from each other; however, the three mean masses are all significantly different from one another.

In the surveys of the German and U.S. Air Forces reported in Grunhofer and Kroh (1975), measures of stature and weight were taken in a comparable fashion as in the NATO survey above, under the guidance of Hertzberg and Churchill who were authors of the NATO report and participants in the NATO survey. While this does not eliminate the measurement technique variability, it should reduce it to a minor factor. The means and standard deviations are provided in Table 1-4 for comparison. These groups appear to be only slightly different from each other but differ greatly from the NATO groups shown in Table 1-3. While the observers were *different*, it is highly unlikely that differences this large could be attributed to measurement error alone.

Table 1-3. Comparative Stature and Mass of Military Personnel from Turkey, Greece and Italy.

	mean	SD	N	mass*	ht*
TURKEY					
stature (cm)	169.29	5.73	915		a
mass (kg)	64.61	8.23	915	x	
GREECE					
stature (cm)	170.51	5.88	1084		b
mass (kg)	67.03	7.62	1084	y	
ITALY					
stature (cm)	170.6	6.23	1358		b
mass (kg)	70.26	8.43	1358	z	

* variables with the same letter have means which are not significantly different at $p < .01$.

Table 1-4. Comparative Stature and Mass of German and U.S. Air Forces.

	mean	SD	N
GERMANY			

stature (cm)	176.88	6.14	1465
mass (kg)	74.83	8.11	1465
U.S.			
stature (cm)	177.34	6.19	2420
mass (kg)	78.74	9.72	2420

Standards

Since the purpose of an international survey is to acquire data for comparison, standardization of the data collection process, and the removal of measurement difference artifacts, is imperative. As mentioned earlier, this is possible with new 3-D digitizing technologies which alleviate the need to use the same observers. Consequently, with new technology it may be possible to update data bases simultaneously and gradually at several locations with collections of smaller specialized groups, rather than with thousands of subjects sequentially as has been practiced in the past.

The rapid advancements in data communications and information management technology will result in users having instant access to anthropometric data from anywhere around the world. For this concept to realize its full potential, the data must be compatible with the various types of hardware and software systems in use. An important step for the 3-D anthropometric community is to establish guidelines and standards for how data are to be structured, formatted, stored, accessed, interrogated, reduced, etc. Chapter VII is devoted to addressing the status of these standards.

The issue of standardization also covers other areas of interest. For example, current standards exist relative to data collection, or measurement processes. These standards essentially define how 3-D anthropometry is performed today. To properly assess how technology will drive changes to the current adopted anthropometric methodologies, one must first understand what the current methodologies are. With this thought in mind, a description of all available DoD, NATO, and commercial anthropometric standards are provided in Chapter VII.

The purpose of this report is to describe the status and need for 3-D anthropometry. A companion report is intended to recommend methods for surveying. A chapter in that companion report will provide recommendations on potential data standards to adopt within the 3-D anthropometry community.

Unique Aspects and Needs of 3-D Surveys

Anthropometric surveys for the collection of traditional anthropometry are well-established and survey data for traditional anthropometry are abundant; the same cannot be said for 3-D anthropometric data. While it is clear that traditional and 3-D anthropometry have different uses and applications, and while the growing need for 3-D anthropometric data is apparent, relatively few 3-D anthropometric surveys have been conducted. The few which were conducted in recent years have been small and the data are limited almost exclusively to head and face anthropometry. However, this limited experience with 3-D scanning has revealed some unique needs.

Three-dimensional surveying will require 3-D landmarking. Many of the traditional landmarks were originally intended only to pin-point one or two dimensions. These will need to be more specific for 3-D.

With 3-D line-of-sight scanning, some important points may be obscured from view, such as the top of the inner arm (axilla). Some method for visualization will need to be devised, such as placing a bar of a known size into the axilla before scanning.

If the scanning takes longer than one second, there needs to be some method for steadying the subject which does not obscure the body from the scanner. Otherwise, movement artifacts will add error to the data sets. Some movement artifacts may be correctable automatically, but some types of movement will not be easily corrected in this manner. For example, whole body sway may be corrected after data collection, but movement of the arm with respect to the torso may not be.

There are some privacy issues which need to be addressed. The type of body covering worn during data collection needs to provide acceptable covering without obscuring or

distorting the natural body surface. Also, the subjects' faces will be recognizable, and this may add to their concern about data use and distribution. For some subjects it may be necessary to either 1) not collect data on the face, or 2) to permanently separate the face from the remainder of the data. Furthermore, some groups of the population may be more sensitive about privacy issues than others which can mean the randomization of the sampling can be affected. This also needs to be addressed in the planning stages.

These are just a few of the unique needs and conditions of 3-D surface anthropometry surveys. More detailed planning is needed. As a result, recommended changes to surveying methodology for anthropometry based upon these needs and conditions, as well as experience with smaller scale 3-D scanning, will also be included in the companion report.

Traditional Measures During 3-D Surveys

It is important to emphasize that 3-D surface anthropometry is not designed to replace traditional anthropometry. Rather, 3-D surface anthropometry adds an additional tool to the tool kit. There are still some measurements that traditional tools capture better, and some applications for which traditional tools will continue to be more cost effective for years to come. For example, tape measures are still the best tools to collect circumferences for selecting a size for an individual at a recruiting station or for home measurement for a mail order. Tape measures are inexpensive and readily available anywhere. If all that is needed is one to two measurements, extracting data from a full-body scan would be very time consuming as well. Furthermore, there is a long history of tailoring experience that is based upon tape measurements. Circumferential measures taken from a scan are not always the same. The 3-D scanner can follow every bump along the surface while the tape will span many of them. Until the translation from the tape to the scan is made the tape measurements will still be needed. Eventually it is possible that tape measures will be replaced by 3-D technology, but it is too soon to abandon them entirely at this point. The challenge will be to determine which traditional anthropometric measures should be included in a 3-D Survey.

Engineering Before and After 3-D Surface Anthropometry

The following example is a walk through an equipment development program. It is intended to illustrate the advantages of using the new technology for the engineering process. The goal of the program is to design a new oxygen mask which will cover the facial region from the top of the nose down to the top of the chin. This mask might be used by an aircraft pilot, or it might serve as the mask for a patient's respirator.

The first step is to create a design concept followed by engineering drawings of at least one size. The first thing to note is that the people it is "designed for" at this point are not necessarily the people it will fit.

For example, in a study of three helmet systems, (Blackwell & Robinette, 1993), the three helmets were each developed by a different manufacturer in a pre-set size "large". The developers believed that this should be a "one-size-fits-all" system. While the helmet designs were very different, the sizes were all designed to the same head sizes. Figure 1-5 below illustrates what population segments the helmets appeared to actually fit after fit testing was performed. The three helmets (A, B, and C) did not fit the region for which they were "designed," nor did these three size "large" helmets even fit the same people. The reason for discrepancy between the design population and the true fit population is that there are many fit factors that are unknown at the design stage.

One of the most important unknowns in the past was the surface contours. As noted in the limitations of traditional anthropometry above, most of the contour information is ambiguous and artistically interpreted. In the design of a positive pressure oxygen mask in the early 1980's the knowledge of the facial contours was determined to be critical but the traditional anthropometry available contained data on only one point within the contact region between the mask and the face. The mask was produced and even after much trial and error, still has substantial fitting problems which are only now

beginning to be identified and resolved using the now available 3-D surface anthropometry methods. The point is that 3-D surface anthropometry can help the designer create a better initial design and get closer to fitting the desired population because the 3-D surface contours are known.

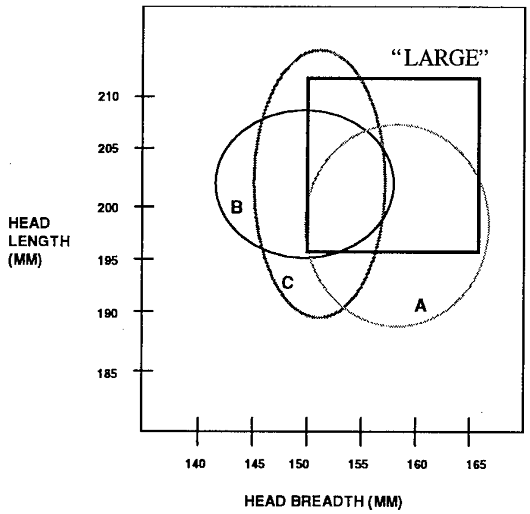

Figure 1-5. Fit regions for three size "large" helmets versus their design size "large."

However, there are other important unknown factors that still remain, such as the amount of offset of the mask from the body, called "ease" in the clothing industry. In other words, the mask will not necessarily fit if it is exactly the same shape as the face, it will need to be smaller in some places and larger in others. A suit of clothes made to match exactly the contours of the body certainly would not fit: it would be far too tight. So the question is, "how much and where should the mask be different?" The answer is not only dependent upon general fit requirements, but also on the particular fit requirements of a given type of mask and a given design. An oxygen mask that will be worn in a fighter aircraft under high-G forces will probably have to fit tighter in some places than a respirator mask for a hospital patient, for example. The location and amount of each offset *can only be estimated* during the design stage. The accuracy of the estimate must be verified with a prototype evaluation.

Therefore, the next phase is to produce a prototype of at least one size in order to verify the fit. The development of a prototype for this oxygen mask is more simplified than its development using traditional anthropometry. With 3-D scans available it is much easier to build the required 3-D models and prototypes. In the development of a pressure glove for a space suit, ILC Dover (Cadogen, personal communication) estimated that a 3-D scan of a hand enabled them to reduce the prototype production time by as much as 60%. This saved them months of work, as well as cost.

Once the prototype is built, it is time to fit test. The fit testing is intended to:

1) establish good item proportioning, 2) establish the range of fit per size and the impact of design trade-offs, 3) minimize the number of sizes, and 4) optimize the design.

There are two required components to the data collection during fit testing, 1) measuring quality of fit and 2) anthropometry. For a mask 3-D surface anthropometry also enables the measurement of the subject in the mask and the spatial relationship between the face and the mask. As mentioned earlier, this ability can be essential for ascribing a cause to a fit problem and arriving at a solution. This can be particularly true for an oxygen mask. In a recent fit test of a positive pressure oxygen mask we found that the traditional measurements alone did not explain why one person got a good fit while another did not. Hence, the traditional measures did not determine the range or anthropometric region of fit in a single size. The change in face contour, particularly around the bridge of the nose, combined with the vertical location of the mask on the nose and the rotation of the mask about the nose were all important factors many of which were not measurable with traditional tools.

Fit test analysis includes: 1) establishment of the anthropometric variables that discriminate fits from failures, 2) separating regional fit problems from overall design problems, and 3) comparison with large samples from the target populations. For the first two steps the ability to visualize the fit is a real advantage. This has been done in the past using still photographs

and video tapes, but these media do not well illustrate fit. With 3-D scanning of the mask and the face the fit can be visually examined in almost "microscopic" detail, and measurements of the offsets or overlaps can actually be taken and directly applied to fix problems.

Comparison with large samples consists of overlaying the region of fit in a single size onto the larger samples. The main purpose is to establish the other sizes needed. It is also possible to project the number of items of each size which should be kept in stock in order to accommodate a given percentage of the user population. Using this information, optimal solution strategies are formulated, and these are compared for cost versus benefit.

One of the solution options might be to make custom fit sizes for a small portion of the population or for the entire population. For a certain type of oxygen mask it may be cheaper to make a custom mask for everyone rather than to maintain a large inventory of sizes. While complete customization may not be the cheapest alternative, customization may still be cheaper and better for small segments of the population who fall at the extremes of a size, or who have special needs, such as a previously broken nose. 3-D surface anthropometry combined with new automated manufacturing technologies are making such customizations increasingly feasible and cost effective.

Without 3-D surface anthropometry, the customization process requires making a cast of the body segment (in this case, the face). A technician would then have to make a mold from the cast. This requires a great deal of artistic interpretation and the resulting molds may vary widely from artist to artist. Quality control was limited before digital information was available. The method described above is used currently for an aircraft pilot oxygen mask. The process from cast to mask takes a minimum of six months.

Using 3-D surface scan data, the information is digital and therefore measurable. Also, 3-D data readily lends itself to the production of 3-D solid models needed for producing the molds by computer numerical controls (CNC) or dipping-forms: much of the production process can be automated and standardized. For an oxygen mask, creation of a mold or a dipping form can now be done using rapid prototyping methods such as stereolithography, laser sintering, or laminated object manufacturing, which can cut customization time down to a few days.

Three-dimensional surface and manufacturing anthropometry can improve engineering processes at almost every stage. 3-D technology promises to improve the quality of the engineering process while making the process more cost effective.

OVERVIEW OF THIS PUBLICATION

This publication is the first of two publications submitted by the AGARD AMP Working Group on 3-D Surface anthropometry. The purpose of this first publication is threefold: 1) to stress the importance and need to continue 3-D anthropometry surveys in the traditional areas as well as new areas of application; 2) to describe the new 3-D technologies available to the anthropometric community and to identify the impacts this new technology has on how 3-D anthropometry is being performed, and 3) to identify areas where work is needed to develop an integrated 3-D anthropometry network for the sharing of information and data. The following chapters are devoted to addressing these issues in one fashion or the other.

Chapter II discusses the various fields of 3-D anthropometry applications along with the common technologies used in each field. The emphasis of this chapter is on applications within the medical field, human systems engineering, and clothing technology. An overview of applications within the fields of comparative morphology and virtual reality are also discussed.

Chapter III describes the various measurement technologies currently available for 3-D anthropometry. Technologies discussed include photogrammetry, videography, surface scanning (lasers and contact devices), and volume scanning. Descriptions of each methodology are discussed along with the significant advantages and disadvantages of each method.

Chapter IV discusses the techniques and technologies used to visualize, model, and analyze 3-D anthropometric data. The discussion covers a wide range of topics including hardware platforms, software systems, and user requirements applicable to 3-D anthropometric data visualization, modeling, and analysis. This chapter serves to highlight the potential improvements in improving the analyst's ability to visualize, retrieve, and analyze 3-D anthropometric data through the use of state-of-the-art computer technology.

Chapter V is a comprehensive overview of current data base and data communications technologies applicable to 3-D anthropometry. Generic and specific design requirements for a 3-D anthropometry data base are discussed. Data communications technologies are also discussed with emphasis on the current networking technologies, communication mediums, and data formats. An extensive discussion on Picture Archiving and Communications Systems (PACS) is also presented as PACS may become the standard for transferring certain data formats applicable to 3-D anthropometry.

Chapter VI focuses on the emerging technologies and concepts in improving the user interface between software systems and the operator. The technologies and concepts described in this chapter, even though directly applicable to 3-D anthropometric software systems, are essentially applicable to all software systems. This chapter describes the basic requirements for the user interface along with application specific requirements.

Chapter VII closes this publication by highlighting the importance of adopting standards for the wide range of technologies used in the field of 3-D anthropometry. The focus of this chapter is on the 3-D anthropometric data generated from the new technologies used. Major issues discussed include data formats, data storage, and exchanging data between multiple users.

The second report will cover more of the procedural aspects of 3-D anthropometry. It will provide information relative to preparing anthropometric survey plans, identifying survey requirements, recommendations for the methods and guidelines to use in conducting the surveys, techniques and procedures for analyzing the survey results, and recommendations for data formats. A major objective of the second publication is to recommend a set of adopted methods and guidelines which will optimize the compatibility and standardization of anthropometry data between multiple user organizations.

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CHAPTER II: APPLICATIONS

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INTRODUCTION

Human morphology has been studied from the time of the ancient Greeks who used it to classify individuals predisposed to certain ailments. Hippocrates, c. 400 BC, postulated two physical types, which he called the phthisic habitus and the apoplectic habitus. Since then many others have tried to classify the human form (see Sheldon, Stevens, & Tucker, 1940). Sheldon and his co-workers further refined human classification into somatotypes. They maintained that the human form is intermediate between three extremes, the endomorph, the mesomorph and the ectomorph. Their classification method involved a series of detailed measurements taken from photographs but there was a significant element of anthroscopy (photoscopic appraisal) involved, in other words, a judgment of the appearance of photographs modified by the measurements. This work has been useful in many fields since it is far more accurate to use a typical somatotype than a simple average.

More recently, size surveys have been carried out, mainly for the clothing trade but with obvious spin-offs in the medical field. These have been direct measurements of the body using tape measures, spreading calipers and other manual measurement tools. For modern tight-fitting garments, more than 40 anthropometric measurements (displacements and circumferences) are desired; limitations include the cost of taking so many measurements and the time that the available subjects are prepared to give. Even if such measurements are taken the data are not sufficient to provide answers to questions involving body shape such as "What is the shape of the leg hole in a swim suit?" Nor are they sufficient to provide accurate three-dimensional (3-D) computer simulation models.

The study of the human body as a 3-D object has only recently begun, starting in 1966 with a technique of light sectioning by Lovesey (1966). This was labor intensive in the interpretation of the data and extremely time consuming. The information gained from 3-D studies can be used in, for example, ergonomics, orthotics and prosthetics design, plastic/cosmetic surgery, obesity studies, the study of breathing and seating design for the disabled. The 3-D shape is dependent on underlying anatomical structures and therefore it is possible to study body shape distortion due to natural and pathological processes. This is of interest for assessment and diagnosis in clinical practice.

The clothing and manufacturing industry is able to use human body shape information for product design and manufacturing. This has been assisted by the recent advances in computer-aided design (CAD) and computer-aided manufacture (CAM), (Jones, West, & Brooke-Wavell, 1993).

Size and shape measurement of the human body is an important source of information. For example, determining the size and shape distribution of a population provides norms for the study of abnormalities or the effects of aging and disease or changes due to body growth and development, seasonal biological variations, or nutritional or pathological conditions.

MEDICAL APPLICATIONS

Introduction

This section reviews a range of medical applications resulting from 3-D surface anthropometric scanning. It deals with the majority of the human body regions which are discussed under their respective headings.

Body Deformity

The term body deformity applies to the deviation of various anatomical regions of the body from the feet to the head in either the saggital, coronal or a combination of these planes. These deformities may be a result of trauma, pathology or occupation, or a combination of these causes. Applications are given under their respective regions:
Head and Neck - Congenital Malformations.

Body deformity or abnormal morphology can be related to congenital, acquired, syndromal disorders

or from unknown causes. A compilation of body measurements using anthropometry is reported in Meaney and Farrer (1986). Craniofacial abnormalities related to fetal alcohol syndrome are reported in Hiritz, Thomas, and Merchant (1986), using close range Photogrammetry.

Glaucoma

Three-dimensional measurement of the optic disk in the early diagnosis of glaucoma is described in Takamato and Schwartz (1985). The technique is now routinely used and found to be highly reproducible and sensitive in detecting changes in cupping of the optic nerve head. Resolution needed is in the order of tens of micrometers.

Orthodontics

Laurendeau, Guimond, and Poussart (1991) and Côté, Laurendeau, and Poussart (1991) have used 3-D imaging techniques to measure wax dental imprints. Segmentation software to process 3-D images is used to automatically measure teeth interstices and the dental arches in cleft palate patients.

Surgery

Most applications reported in this field are related to maxillo-facial surgery. Three- dimensional imaging techniques are used to digitize the subject's facial morphology. Computer graphics tools allow visualization and editing in order to evaluate surgical strategies. Vannier, Pilgram, Bhatia, and Brunsden (1991) use a multi-camera multi-projection system to digitize patient shapes in less than a second. Images are taken a few hours before the operation, 24 hours after, and 2 weeks later to objectively study facial plastic surgery.

Linney and co-workers (1989, 1992) use both laser scanner for 3-D imaging and CT data. Various editing tools have been developed to computer simulate surgical procedures. Applications reported are facial reconstruction, cranioplasty and ear prosthetics. Two laser scanned images taken before and after surgery can be registered and subtracted to demonstrate soft tissues changes. Accuracies of better than 0.5 mm are reported (Moss, Grindrod, Linney, Arridge, & James, 1988).

Coombes, Moss, Linney, Richards, and James (1991) describe a surface patch model used to analyze the facial geometry. They discuss surface primitives based on mean and Gaussian curvatures which are used for segmentation. These authors suggest using this method for the development of normative standards for facial aesthetics.

Thorax

Many devices are designed to measure the back of the torso to assist with the diagnosis of scoliosis (Meadows, Johnson, & Allen, 1970; Turner-Smith, 1982). A commercial system developed by AXIS Software Systems Ltd. (Schofield, 1988) can digitize either the back or the front of the body. A detailed review of this field of research can be found in the proceedings of bi-annual symposia dedicated mainly to spinal deformity diagnosis using surface topography (Moreland, Pope, & Armstrong, 1981; Drerup, Frobin, & Hierholzer, 1983; Harris and Turner-Smith, 1986; Stokes, Pekelsky, & Moreland, 1987; Neugebauer & Wendischbauer, 1990). Occupational postural deformities have also been studied, e.g., an assessment of injuries among violinists (Halioua, Liu, Chin, & Bowins, 1990) and a study of postural asymmetry related to chronic back pain (Swain, Daunt, Robertson, & Isherwood, 1986).

Lung Function Studies

Similar measurement technologies (close range Photogrammetry) have been used to study breathing and respiratory mechanics. Projected patterns to extract volume changes and velocity of surface point displacements are reported in Kováts, Böszörményi-Nagy, and Ôrdîg, (1988). Lewis and Sopwith (1986), described a method using an array of dots to measure the anterior and posterior surfaces of the thorax for lung function studies. Clinical diagnosis in the breathing-pump mechanism is proposed along with potential applications in pediatrics, sports medicine and ballet-choreography. Respiratory mechanics are analyzed in the context of the measurement of vital capacity. Other studies related to growth and aging effects are discussed in Kováts (1985b) and Adams, Rüther, and Klein (1988). Gourlay, Kaye, Dennison, Peacock, and Morgan (1984) propose solutions to hair interference, shadow effects and patient motion.

Breast Topography

Malignant lesions have been studied by a measurement method to quantify breast volume and volume distribution (Sheffer and co-workers, 1982, 1985). Asymmetries in volume distributions have been correlated to lesion detection, but are not considered sufficiently sensitive and specific to warrant clinical use.

Jones, West, Harris, and Read (1989) describe how their 3-D scanner (LASS; see Figures 2-1 and 2-2) monitors breast surgery (mastectomy as a result of breast cancer). The subject is scanned before and after surgery. Pre-operative data are used to manufacture a bespoke prosthesis that restores the original outer appearance of the removed breast tissue. This ensures better fit and comfort which is essential for psychological rehabilitation of the patient.

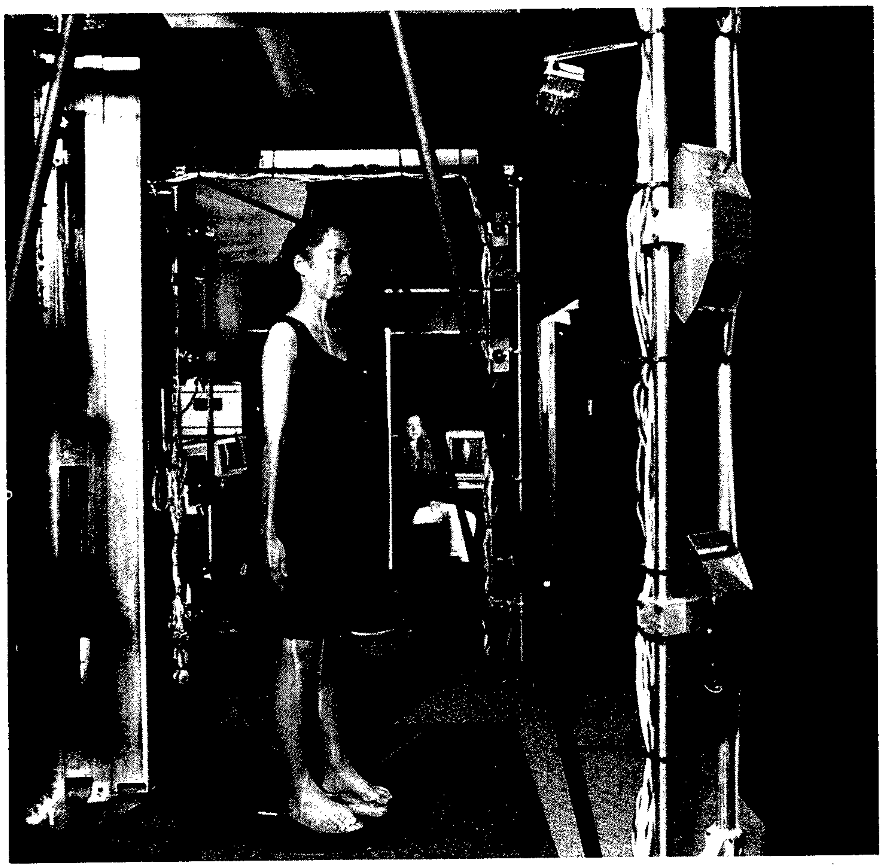

Figure 2-1. A subject being scanned in the LASS experimental rig. The narrow vertical slits of the projector light are falling on the body contours.

Pediatrics

The main objective of the research in automatic diagnosis of scoliosis is to mass screen children in an attempt to produce an early diagnosis before too much damage is done to the body structure. School screening using moiré photography has been reported by Neugebauer and Windischbauer (1987) and the cost analysis of this approach has been discussed. The challenge is in the automation of the diagnosis process. Batouche (1992) presents a knowledge-based system and 3-D reconstruction to achieve automatic diagnosis.

Mehta (1981) suggests that associated facial asymmetries could be used to make a very early diagnosis of scoliosis. Related research on the growth process in childhood (Jensen & Nassas, 1985; Jensen, 1986a, 1986b, 1987) provides data to model normal growth. More recently, Richtsmeier (1993) described a model for predicting a child's skull growth. Computer tools have been developed to compare a simulated (or grown) skull to samples of head images of normal and abnormal children of an age/sex/ethnic population that matches the patient. Moss, Linney, Grindrod, and Mosse (1989) have taken a very unusual set of 3-D measurements. They were able to compare face plaster casts of a subject taken over a period of more than 50 years. It is also noted that plaster induces substantial deformation of tissues (~ 1 cm) due to the weight of the plaster.

Orthopedics

Assessment of foot disorders using stereophotogrammetry is reported in Craxford, Rutherford, and Evans (1981). Monitoring recovery after surgery has also been evaluated by Houghton, Jefferson, Thomas, Harris, and Turner-Smith (1987).

Figure 2-2. Anterior and lateral views of part of a subject scanned in high resolution (i.e., vertical slices taken in 2.5° increments at 5 mm horizontal cuts).

Twenty-nine patients were assessed by X-rays and surface scanning both before and after surgery for scoliosis.

Custom Prostheses for Dentistry and Orthopedics

Application of 3-D anthropometry to achieve function and fit is well established in orthotics and prosthetics. Specialized sensing components produce measurement sets that are subsequently processed to manufacture customized orthotics or prostheses.

Three-dimensional imaging has been used mainly for fitting artificial limbs and dental restoration. In each case a detailed 3-D map of the receiving part is used for the production of a negative shape that will interface the prosthesis to the subject's body.

Duret and Blouin (1986) developed a complete process for tooth -crown fabrication, from in situ optical recording to Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) interface, modeling and manufacturing. Challenges are related to multiple view registration, data shape modification for cement and the generation of a CAM file for machining. A similar application is described in Yeung et al. (1990) where the in situ recording is replaced by the scanning of a dental impression to transfer the shape. CAD/CAM technology is used to generate a tooth-crown with an accuracy of 25 μm.

A commercial product (CEREC) for the automation of the production of inlays has been available from Siemens since 1989. It uses an in situ optical probe to digitize the site and a compact milling machine to carve the final shape. Titanium oxide powder with a wetting agent is also used to enhance optical measurements. Accuracy is in the order of 100 μm. A 20-μm resolution 3-D imaging system for in situ measurement has been reported by Altschuler (1990).

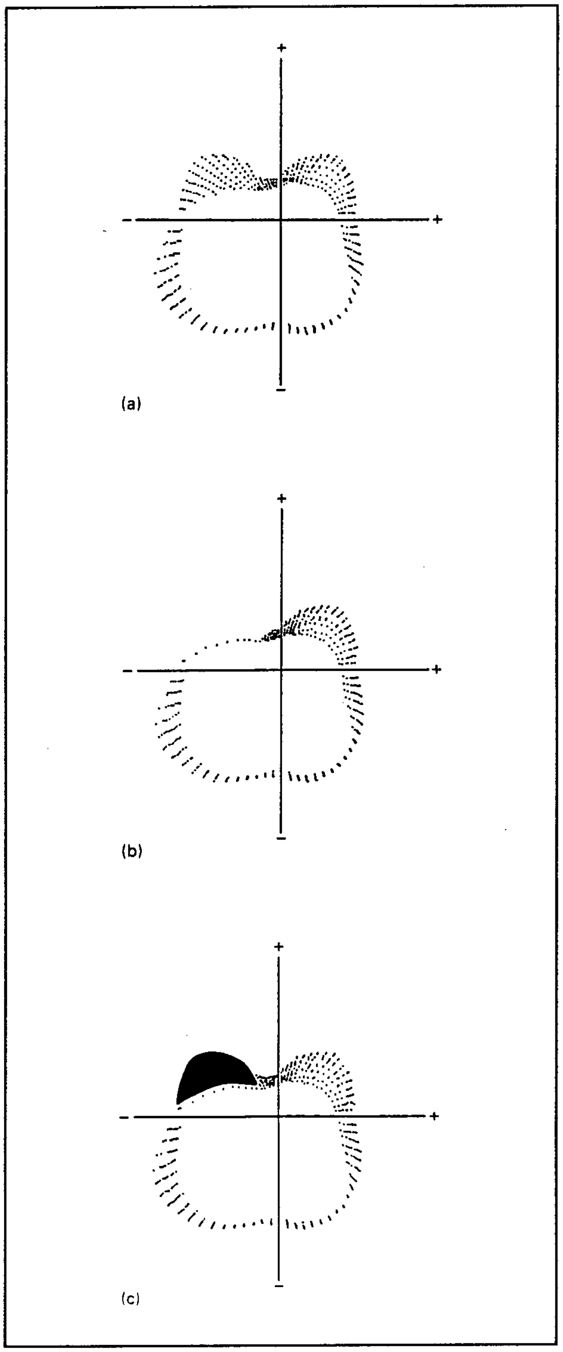

Figure 2-3. Cross-sectional slices through the maximum chest circumference of a subject in three conditions: (a) pre-operative; (b) post-operative, following simple mastectomy; (c) shaded area indicates size, shape, and volume required for breast prosthesis, calculated from LASS scan data.

It uses a space-coded structured light approach to image the shape of the teeth. An intensity image is also digitized to help the user interact with the data in providing visual cues. The main problem with teeth imaging is the resolution, which must be very high (~20 μm) for good matching.

In contrast, for limb prostheses, the resolution needed is relatively low, but soft tissues which surround the residual limb complicate data analysis. Proper fitting is not only related to the exterior skin surface, but depends heavily on underlying bone structure, which cannot be measured optically. Saunders (1982) and Duncan (1986) describe a complete system that optically measures the shape of the stump, transfers the data to a CAD system for editing and formatting and produces a CAM file for NC machining of the prosthesis. An improved optical measuring technique has also been described by Halioua, Liu, Bowins, and Shih (1992). It uses a technique called phase-measuring profilometry to digitize the stump.

Prototypes of computer-controlled prostheses have been designed and manufactured by CAD/CAM technology (Pho, Lim, & Pereira, 1990). The basis for using CAD/CAM techniques in prostheses design is a laser surface scanning device captures the geometry of the affected body part. The processed 3-D data file is then interfaced with a CAD modeler where reconstruction, mirroring, scaling, etc., can be performed. The resultant CAD model is then passed on to CAM, which concentrates purely on producing a "positive core" for molding the prosthetic device (Bok et al., 1990). See Figure 2-1. Computer-Aided Design and Computer-Aided Manufacturing techniques, though often technologically associated with engineering and applied sciences, are central to the practical implementation of 3-D Anthropometry.

Medical Management

In this field of application, accurate data on the volume and/or surface area of the human body are desired to allow the physician to manage homeostasis or drug administration with precision. The measurement of body surface area (BSA) in children of ages between 3.5 and 15 years, with liver disease, by a novel 3-D body scanning device is reported by Jones, Baker, Hardy, and Mowat (1994). Their study showed that this type of whole body imaging was acceptable to young children (precision 1%). It is interesting to note that traditional anthropometric equations for estimating BSA in children (Haycock, Schwartz, & Wisotsky, 1978) overestimates by 10% when compared to the accurately calculated BSA from 3-D scanning. The clinical implications of this are

clinical implications of this are discussed in relation to drug dosage and medical management.

A structured light approach to body surface area and volume measurement is reported by Dunn, Keizer, and Yu (1989). Camera calibration and surface modeling are discussed in detail. Resolutions of better than 1 mm are obtained. The author suggests applications related to the measurement of the surface area of burns, swelling in arthritis, expandable tumors and for planning of radiation therapy.

Karras and Tympandis (1982) have also used 3-D measurements to monitor shape variation during pregnancy. Measurements of area and volume of the abdomen, breasts, buttocks and thighs have been made at regular intervals during pregnancy and after delivery.

Medical Science Education

The development of electronic anatomical teaching atlases of the human body is now becoming an extremely active area of interest within universities and medical schools. Also being developed, and gaining considerable interest, are highly-interactive multi media atlases that integrate detailed graphics to enhance the knowledge and communications capabilities of students and professionals within the scientific and medical communities. The simplest of these use an analog videodisk to store pre-computed image sequences. Much more general and complex digital 3-D systems have been constructed. We anticipate that these will evolve to become central to the user interface for future 3-D anthropometry systems. The matching of atlas data sets with individual scan volumes has recently been reported.

A recent software release is a program called Animated Dissection of Anatomy for Medicine (ADAM), from ADAM Software, Inc. This is a highly interactive multimedia program of human anatomy which integrates very detailed graphics with intuitive operation. It is made up of a core program with optional modular extensions and the ability to modify or add to the anatomic images using either studio tools or other electronic atlases. One particular novelty is the facility to archive and link 3-D images from body scanning , whether its structured light surface , CT, NMR or ultrasonic scanning.

The "Analog Videodisk Atlas of the Head" is an interactive visualization of animated images through a computerized 3-D full color model of an unstained cadaveric human head. Serial full color images were taken of the blockface of a cryomicrotomed frozen human head ever 200 microns. From this series of images a 3-D digital model with a resultant pixel resolution of 200 micron (Jones et al., 1993) was created using this database, and resampled images were computed along orthogonal axes and written sequentially to a write-once-read-many times (WORM) videodisc unit. Playback of this customized videodisc data set provides animations of the digitally reconstructed surface models. An interactive interface to the animated sequences is provided through a PC-based tutorial package. This tutorial program is able to access videodisc frames to display animations and labeled still images in a software window to illustrate various neuroanatomic topics. The technique of animation as applied to this high resolution 3-D model provides insight into complex spatial relationships and has great potential in research and as a teaching tool (Narayan, 1992).

Miller, Christensen, Amit, and Grenander (1993), have reported on their mathematical textbook of deformable neuroanatomies. Here they show how mathematical techniques are used to transform digital anatomical textbooks from the ideal to the individual, allowing for the representation of the variabilities inherent in normal human anatomies. The ideal textbook is constructed on a fixed coordinate system to contain all of the information currently available about the physical properties of neuroanatomies. This information is obtained via sensor probes such as magnetic resonance, as well as computed axial and emission tomography. Human variability associated with individuals is accommodated by defining probabilistic transformations on the textbook coordinate system, the transformations forming mathematical translation groups of high dimension. The ideal is applied to the individual patient by finding the transformation which is consistent with physical properties of deformable elastic solids, which brings the coordinate system of the textbook to that of the patient. Registration, segmentation, and fusion all result automatically because the textbook carries symbolic values as well as multisensor features.

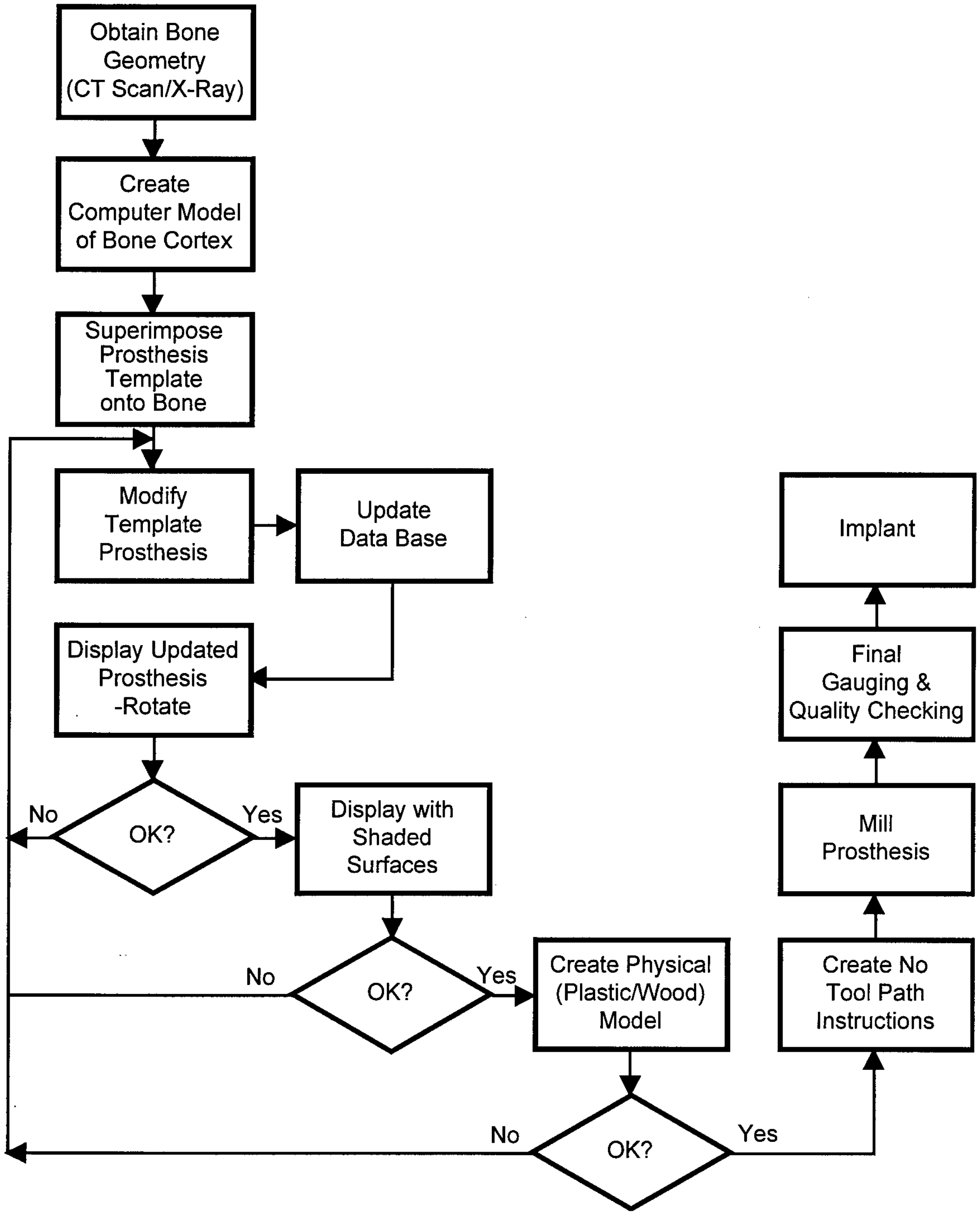

Figure 2-4. Flowchart of Design Process for Patient-Specific Prosthesis

Sports Medicine and Biomechanics

Knee motion studies using 3-D measurements are also reported in Huiskes et al. (1985), Bougoss and Ghosh (1985), and Costigan, Wyss, Deluzio, and Li (1992). Applications cover articular cartilage biomechanics, analysis of joint contact regions, artificial joint design and anthropometric measurements. It is noted that the studies of such anatomic-physiologic movements are essential for the therapeutic and surgical treatments so frequently needed to treat athletic injuries.

Finally, Roebuck (1992) gives suggestions for future developments in the fields of anthropometry, computer modeling of the human form and electronic imaging of the human body. The author stresses the importance of measuring the location of joint centers of rotation and the developing of standards for dividing up body parts for mass properties of moving segments studies. He suggests a very interesting strategy for compact mathematical data description and storage of electronic images, based on a skeleton reference axis and a cylindrical coordinate system for compact surface data representation.

HUMAN SYSTEMS ENGINEERING

Introduction

Human Systems Engineering is the design of "systems" for people. These systems include such things as: extravehicular (EVA) suits for astronauts, computer work stations, anti-g suits for military aircraft pilots, office furniture, football helmets, ski goggles, hiking boots, automobiles and aircraft, toxic hazard protection suits, fire-fighters suits, cold weather gear, ejection seats, video display units, manufacturing work stations, hand tools, etc. as well as combinations of systems.

A key role of anthropometry with respect to human systems is in sizing, shaping, and configuring the systems so that they accommodate or fit the people who will use them. Another, often overlooked, role of anthropometry is in the evaluation and design of the systems for other factors. There are many different "human factors" in the design of human systems. For example, there are issues of perception and information display, training, thermal tolerance, fatigue, and workload in addition to body size, shape and posture. These factors are often interrelated. For example, Jaschinski-Kruza (1988) indicates that continued focus on an object that is closer than the eye's resting distance may lead to fatigue. Kroemer (1993) indicates that the closer a computer monitor is to the eye the lower it should be. So eye fatigue is not just dependent upon screen colors, intensity, etc., but is also dependent upon the anthropometric measurements determining eye position, such as seated eye height.

Another example was demonstrated in a study of helmets with night vision goggles (Blackwell & Robinette, 1992). In this case, the placement of the goggles with respect to the eye affected the sharpness of the image as well as the amount of helmet shift which would result in loss of the image. Consequently, subjective tests of the optical performance of the goggles were influenced by: a) 3-D placement of the goggles with respect to the subject's eyes, and b) stability of the helmet on the head. These were, in turn, influenced by the size and shape of the head versus the size, shape and adjustability of the helmet. Therefore, subjective testing of optical properties of the goggles required measuring and experimentally controlling the anthropometry factors.

In industrial as well as in military environments, the realization of ideas and objectives are achieved most of the time by the actions of the hands, through the use of tools and control knobs or grips. Every day we need to use our hands to operate a variety of devices, such as door handles/latches, locking devices, sink/shower controls, appliance controls, vending machines, desk/dresser drawer handles, elevator buttons, telephones, transportation vehicle controls, computer keyboards and remote controls.

Protective gloves for agricultural workers are studied in Tremblay et al., (1992). It is observed that anthropometric data for this population of workers differs from that for the military personnel population, on which the glove manufacturers base their designs. It is also noted that some subjects prefer tight fit while others find it unacceptable. Nineteen hand dimensions were collected on 380 Albertan grain farmers who handle pesticides. Suggested considerations for design are gender, age, ethnic origin and occupation. It is stressed that military needs and requirements often differ significantly from other occupations and that a fitting study must take that parameter into consideration. This also points out the need for anthropometric data on special populations which can effectively be compared to others taken by different people at different points in time.

There are some anthropometry needs that are specific to the type of human system, and there are also data

and analysis principles that apply to all applications. This section is consequently divided into three sub-sections: 1) general applications, 2) work and living spaces, and 3) clothing and protective gear.

General Applications

All size and shape representations beyond one dimension require models to characterize the relationships between measurements. The model can be mathematical or statistical with no human anatomy visualization. These models are intended to either describe, predict or otherwise analyze geometric and mechanical behaviors. A classic example of this was described by Hanavan (1964).

A model can also be a visual characterization, such as human figures in drawings or computer models, or a physical characterization such as department store mannequins, plaster head forms or crash test dummies. These can be of two types: 1) graphical representations or sculptures with no statistical or mathematical anthropometry, or 2) graphical representations or sculptures which are made to some statistical or mathematical criteria. Examples of the latter type include the helmet head forms described by Zeigen (1960), drawing board mannequins such as those described by Woodson (1954), Dempster (1955), and Kennedy (1980), crash test dummies such as ADAM (Oleson, Rasmussen, & Plaga, 1993), clothing and equipment mannequins such as those described by McConville et al. (1963), and, last but not least, computer models. Hickey et al. (1985) identified 37 different man modeling programs for CAD, and that number does not include the more recent models, such as Mannequin ™ by Biomechanics of America , and JACK (Badler, 1989).

The amount of data and the quality of the characterization of data in a graphical or physical model is extremely varied. Often the best looking graphics or animation are associated with the least data. This is due to limitations in; 1) statistical methodologies, 2) the type of measurements taken, and 3) computing capabilities. Each of these limitations are explained in more detail below.

The first models were single individuals, often the engineer or designer him or herself. This type of model is still commonly used by entrepreneurs for developing a concept or a prototype, and it can be very effectively used for this purpose. It is generally not a very good model for characterizing the population, since, the arbitrarily selected model of this type can be very atypical. A recent example was that of an anti-g suit which was prototyped around the engineer who created the concept. This engineer happened to have one knee several inches higher than the other. So while the suit fit this person quite well, it wouldn't fit anyone else.

The first attempts at characterizing populations using statistics utilized the mean values, in other words, "the average man" concept. One can imagine the customer requesting equipment or clothing "designed for the average guy." There are several problems with this approach, one of which was humorously illustrated by Damon et. al. (1966) by showing a man attempting to walk through a doorway designed to the average stature. A doorway of that size would be too short for 50% of the population.

The realization that the average or 50th percentile would exclude too many people lead to the desire to characterize a range of people. As a result the next statistic which became popular was the percentile. Percentiles are univariate statistics and as such are not good for representing more than one measurement. The more of them used in a single model the worse the error. Unfortunately, this was not immediately recognized, and crash test dummies were constructed in the 1960's (Hertzberg, 1968) using percentiles for several measurements. Some of the apparently heated discussions that ensued are recorded in the bulletin of the Motor Industry Research Association of England. Searle and Haslegrave (1969, 1970) explain the problem with the use of percentiles quite clearly, pointing out that a 15-inch neck length does not occur in nature. One of the key problems is that percentiles are not additive. This means that while they were maintaining the 95th percentile for some measures they were as a result distorting other areas beyond the range of reality, in this case very apparently in the neck.

Researchers in the 1960's were somewhat handicapped by not having computer graphics or rapid prototyping capabilities to assist them, and computers were quite computationally limited at that time as well. It is much more surprising that percentiles are still commonly misused to this day. Alternatives to percentiles for representing humans began appearing in the literature in the 1970's. One of the first attempts was a study by Moroney and Smith (1972), who attempt to characterize percentages of the populations from a multivariate perspective. Series of least squares regression equations have been used to: 1) estimate pattern piece proportions for clothing (Tebbetts et al.,

1979; Robinette et al., 1981a; Robinette et al., 1981b; Robinette, 1986; and Robinette et al., 1990), 2) estimate body segment sizes, volumes and mass properties for use in other models (McConville et al., 1980; Robinette & McConville, 1982; and Young et al., 1983), and 3) to compare the body proportions of different populations, among other things.

A newly emerging type of mathematical model for human systems engineering is the "multivariate model" or series of models such as CADRE (Bittner et al., 1986), and models reported by Haslegrave (1986), Hendy (1990), and Zehner et al. (1993). Late in the 1980's computer tools for creating and using new multivariate statistical representations began to appear (Hendy, 1990; Robinson et al., 1992). These are packages specifically created to multivariately address the design of equipment for humans.

So what is the continued attraction of percentiles? One explanation is that percentiles are simple and give the misleading impression that a specific range of people will be accommodated if they are used. Zehner et al. (1993) clearly illustrates the fallacy of this concept by showing the reduction in the number of people accommodated with each additional percentile range. Figure 2-2 below is extracted from that report.

Another explanation for the continued widespread use of percentiles is the fact that percentiles are easy to list in tabular form in paper text. Multivariate data are impossible to portray for every use in tabular form. Even books of bivariate plots require hundreds of thousands of pages to get every combination of every pair of variable in a single survey. In other words, the alternatives to percentiles require complete data sets, on-line, with statistical analysis, visualization and expert assistance, i.e. a data management and analysis system. This will clearly be a need for 3-D surface anthropometry as well.

The modelers that understood the problems with percentiles were still faced with the task of taking lists of measures and creating the 3-D objects. Attempts at doing this illustrate that despite the hundreds of measures on thousands of people captured in some traditional anthropometric surveys, the data sets provide very limited information, requiring modelers to use educated guesses and artistic interpretations to arrive at their models. Body segment link systems, measurement locations, movement, and contours are all poorly defined and measured with traditional methods.

Some research has been done to establish a relationship between traditionally measured body dimensions and mass distribution on living subjects. A series of conferences on "Biostereometrics" [Coblentz and Herron (1985)] were conducted discussing this research. Stereophotogrammetry was used for capturing the surface and calculating volumes, and traditional anthropometry was also collected on the same samples. (McConville and Clauser, 1980; McConville et al., 1980; Young et al., 1983). The information calculated from the stereo photos could then be linked to the traditional anthropometry using statistical tools such as least squares regression. In at least two studies (McConville et al., 1980; Young et al., 1983) least squares regression equations were calculated for predicting mass distribution characteristics of the total body and its segments from the traditional measures. The two studies used 31 male and 46 female subjects.

Work and Living Spaces

Percentiles and regression estimates have been used widely to characterize the human in the work space for design. The problems with percentiles were expounded upon above. The difficulty with regression is that the designer must determine the independent variables and select values to input. All predictions then tend toward the mean. While the predictions are additive (provided a single sample is used to derive the equations) this method can still result in exclusion of large segments of the population. For example, if the designer selects stature and weight as the independent variables, and three sets of values to input: 1) small for both, 2) average for both and 3) large for both, the people who are tall and skinny, and short and fat are not represented. The values input into the equation all fall along a line, but people aren't scaled up and down versions of each other.

A good example of this problem was recently illustrated with the evaluation of an aircraft designed around the small to large concept. According to G. Zehner (personal communication, June 15, 1995), researchers determined that the yoke (the yoke is similar to the steering wheel) could not be fully turned without hitting the thighs of the operator for 30% of the white males, 80% of the black males, and 90% of the females who would qualify to fly the plane.

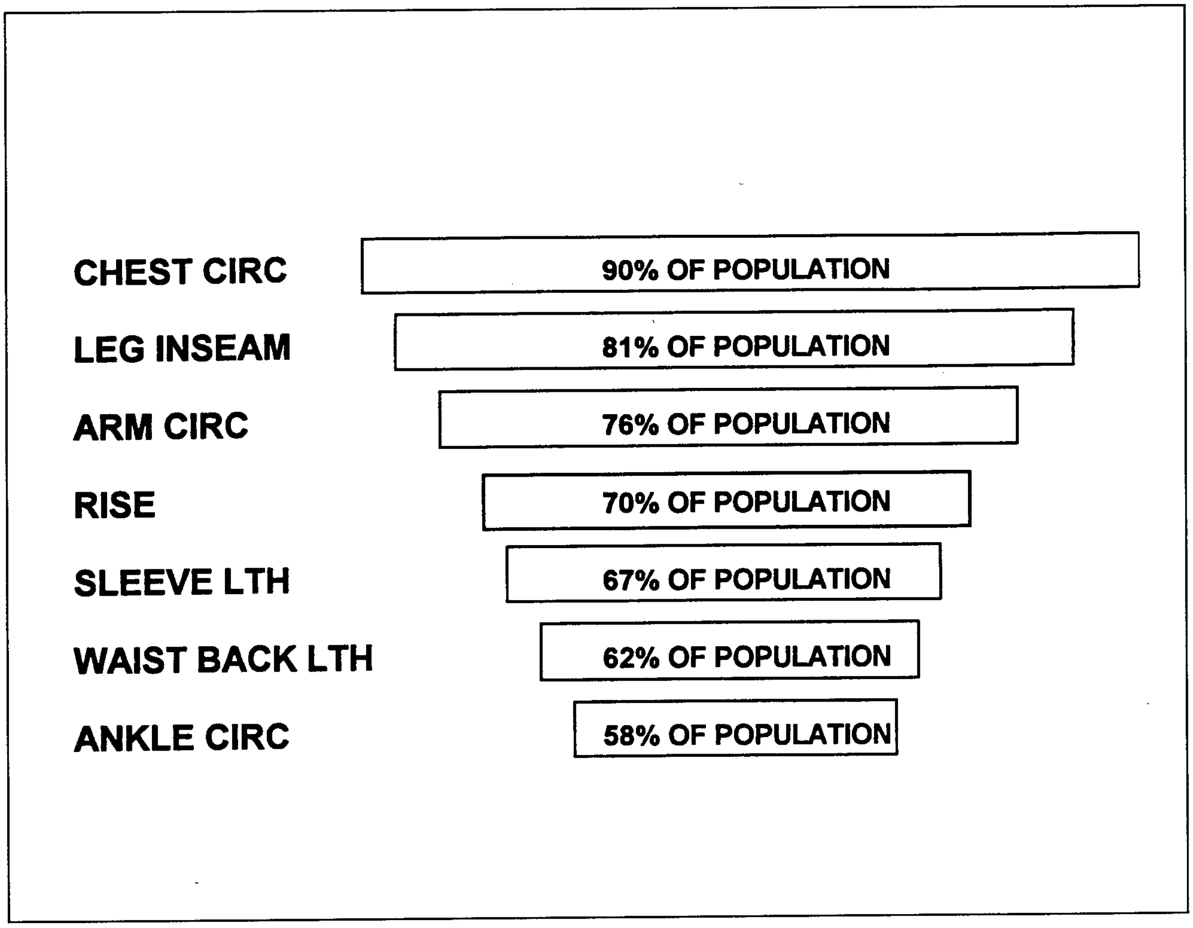

Figure 2-5. Reduction in percentage accommodated with each additional variable.

People with short torsos had to fly the plane with the seat raised fully up so they could see over the nose of the plane. If these people also had either long legs or large thighs they would run into this problem. This problem could not be detected if only short torso, short legs, and small thighs are used.

This indicates the need for some method to better characterize the multivariate variability of the population, and Zehner's most recent work was initiated to meet this need. Zehner is now using live subjects elected for body proportions along principal component axis. During the mapping, the body proportions are changed either with additional subjects or with the aid of extenders, such as blocks under the feet, until the limit of reach or function is achieved. The body measurement combinations which characterize the limits for the aircraft can then be "mapped" against the multivariate distributions of the population. At present the mapping is in only the traditional anthropometric measurement space. In other words, there is no 3-D geometric map. To extend this to future designs, one needs to graphically, mathematically, and geometrically characterize this in 3-D space.

Czaja (1983) noted that a significant amount of the population falls in the category of people having hand disabilities (~3 million in the USA). He stressed the importance of gathering anthropometric data, not only for the adult able-bodied population, but also on a variety of users, including children, the elderly and persons with difficulties in handling and fingering.

Examples of people with hand disabilities are given; they are arthritics, amputees, rheumatoid patients, burn victims and persons with muscular dystrophy, cerebral palsy, multiple sclerosis and Parkinson's disease. Also included in this are people with hand size extremes. The authors suggest that more data

should be available to designers for the evaluation of hand controls design.

The main difficulty, though, is that abilities and task performances are substantially affected by the properties of the glove material and the fit of the gloves (Robinette et al., 1986). In a sense, the person using gloves is closer to the hand-disabled population than the able population. This suggests that a better match between hand controls and a protected hand using gloves could be achieved by improved hand control designs and glove designs.

Clothing and Protective Gear

Different types of clothing and protective gear applications include construction worker safety, motorcycle, football, baseball, diving, welding, riding, fire fighter, protective crash, wrestling, explosive ordinance disposal and flight helmets. Similarly, face masks are used for cold protection, surgical and medical procedures and anesthesia. They are used by dentists, sculptors, scuba divers, welders, fire fighters and others.

Protection of the individual is one of the performance needs for clothing and protective gear but many items must do more than passively protect.

In the case of an aircraft pilot the helmet is used not only for personal protection but also for interfacing with the aircraft controls and instruments. Hall and Campbell (1992) describe the helmet of the future, showing the complexity of the design task and the importance of integration for lightweight design and comfort.

A good review of human factors and safety considerations of instrument helmets, can be found in Rash et al., (1990). This paper discusses a helmet equipped with a night vision system for operation in darkness or under adverse weather conditions. A large variety of topics are analyzed, such as sensor inputs, display parameters, temporal characteristics, visual acuity, field of view, environmental considerations and the effects of internal/external sources of information. Accident experiences are also carefully analyzed in the context of an improved process of helmet design.

The point is that the fit of an item is dependent upon the anthropometry and includes much more than just comfort. It affects the performance and safety of the system. Fit itself is therefore an integral part of the performance. Designers naturally want to achieve the best fit possible so that they will get maximum performance. Past practice has been to pre-determine the number of sizes and the anthropometric measures to be accommodated in each size, prior to development of the item. There have been two basic methods for doing this: 1) start with a base size and use grade rules to predict other sizes and 2) "anthropometric sizing." The first of these has commonly been used in the clothing industry. Robinette and Annis (1986) describe the problems with this approach. The sizes are just smaller and larger versions of the same type. Robinette and Whitestone (1992) give an example of the level of accommodation that can (and cannot) be achieved with this approach for uniform clothing items.

The second method, anthropometric sizing, at the outset appears to be more scientific and to account for more body type diversity. One of the first examples was a study done by O'Brien and Shelton (1941). In this study, thousands of women were measured. They were then classified by "body types," and these types were then divided up into discrete intervals called sizes. Measurements for each size were presented.

Randall et al. (1946) was among the first to use body measurements to derive sizing schemes for flight equipment, after many fitting problems surfaced during World War II. Flight equipment was very specialized with unique fit and other performance requirements. Unlike clothing there was no tailoring history upon which to draw "rules of thumb" for these new types of items. Anthropometric sizing became routine business for the military organizations of several countries. Emmanual and Alexander (1957) used height and weight to separate people into six sizes for anti-g suits. The other relevant measures were estimated from means and standard deviations for the men who fell within an interval. The particular points used on the normal curve varied depending upon the measure. Similarly Zeigen et al. (1960) used head circumference intervals to divide up the anthropometry into sizes for helmets and Emmanual et. al. (1959) used face length and lip length to divide up the anthropometry into size categories for an oxygen mask. Alexander et. al. (1979) and Tebbes et. al. (1979) used height and weight to categorize people for flight suits for men and women respectively. Anthropometric methods were used to develop "unisex" sizing schemes as well. Robinette et. al. (1981) developed unisex schemes for a fatigue type uniform, and Robinette

and Annis (1986) developed a scheme for chemical defense gloves.

A key drawback to both the anthropometric sizing method and the base size and grading method is that most of the important information is pre-set before it is known and costly errors result. The information pre-set includes the number of sizes, the range of fit within a size and the key variables for which diversity is to be represented. As a result they:

1. waste money on unneeded sizes.
2. repeat design mistakes on multiple sizes.
3. imply anthropometric regions of fit which are incorrect.

Mellian et al. (1990) provide an example of a uniform sizing scheme for which fit testing revealed both that there were duplicate sizes that were not needed, and diversity of sizes that were needed but which were not represented. Robinette et. al. (1990) describes a sizing method derived after fit testing prototypes that fits a more diverse population without increasing the number of sizes. These results demonstrate the need for testing prototypes as part of the development process. As explained in Chapter 1, the need for this is due to the fact that there are too many fit unknowns at the design stage.
Many examples of fit testing can be found in the literature. However, it is usually not done until after the item is developed.

Oestenstad et al., (1990) uses fluorescent tracer aerosol at the leaking sites of respirators to study their distributions. Seventy-three subjects are used to link anthropometric data with leaks. Conclusions are that 79% of the leaks occurred at the nose, 73% of leaks approximated the shape of a slit, there is a difference between the sexes, there is a significant association between facial dimensions and leak sites, the amount of leakage is higher through the chin area, and finally, that there is a correlation between facial dimensions and fit factor for three facial dimensions, none of which are used for the design of the respirator.

In a paper by Zehner et al. (1987), a fit evaluation of an armor vest is done on 37 females. Here again the idea is to correlate anthropometric data with fitting parameters. Observations are made on subjects standing, sitting and moving around in various ways (bending and twisting). Such investigations show the importance of measurements and testing at the designing stage. Compromises must be made and it is within the context of the specific use of the garments that decisions must be taken.

One of the reasons that testing of prototypes early in the design process has not been used effectively is the amount of time needed to produce suitable prototypes. However, computer controlled prototyping processes have been developed and researchers are beginning to explore the use of these processes for both equipment and clothing.

Hidson (1984) describes experiments using CAD/CAM technology for the design of a respirator face piece. The geometry is constructed using bi-parametric cubic patches and a 3-axis NC milling machine cuts the final shape.

Hidson (1991) reports a new set of anthropometric dimensions which are suggested for glove design. Fifty dimensions that can be measured by traditional techniques are proposed. The selection of those new measurements is dictated by CAD/CAM requirements. The advantage of the approach is a better match between CAD shapes and hand shapes. Still this requires extrapolation from 2-D traditional measures to 3-D.

For clothing design rapid prototyping concepts are being proposed for creating custom garments as well. Two basic strategies have been proposed. The first is based on templates; a measuring system identifies and classes individuals in relation to these templates (interpolation is used to adapt the predefined patterns to the measured data). The second is based on the development of 3-D surfaces to conform to the human shape.

Quattrocollo and Holzer (1992) are developing a 2-D template-based system where the individual data input is provided by an orthogonal silhouetting method. Back lighting and TV cameras are used to acquire full body silhouette profiles that are compared with templates. The authors have a global approach about custom clothing and anthropometric data collection for the clothing industry. It is proposed to collect cumulative anthropometric data in a database and use a computer network to share the information among manufacturers. This would give them a better knowledge about their target populations. Advantages listed are reduction of unsold stock, improvement in stock management, reduction of manufacturing times, smaller retail selling spaces and inventories, and finally, increased client satisfaction.

A 3-D version of that concept is under development in the US (Halioua et al., 1992), the UK (Jones, et al., 1989; 1993), and Japan (Uesegi, 1991). Structured light is used to digitize the shape of the human body in the context of computer-integrated manufacturing in the textile industry. Many challenges remain, such as the automation of assembly and sewing operations and all importantly, the 3-D design and manufacture of garments.

In terms of data acquisition, it takes from a few seconds to a few minutes to collect the raw 3-D coordinates and the dimensional resolution is typically a few millimeters. Filtering and processing are needed to remove measurement artifacts and to complete the data set for 360° surface description, (Jones et al., 1995). It is interesting to note that today there are no systems (except tomography) that can digitize the whole surface of the human body. Indeed, the human body shape is so complex that it would take an impractically large number of cameras to prevent any occlusion, even then there are re-entrant areas such as the inside of the arms that are virtually impossible to reveal.

Translation of 3-D data points and surfaces into a pattern is another challenge. Okabe et al., (1992) discuss the development of a simulator that estimates the 3-D form of a garment put on a body form. The approach involves 2-D to 3-D and 3-D to 2-D processes. Parameters considered are the anisotropy of the mechanical properties of the cloth, contact and friction with the body, geometrical nonlinearity deformation and optical properties for graphic visualization. It is noted that the 3-D to 2-D process is an inverse problem that requires an interactive approach involving the user through a graphic display.

Hinds et al. (1991) present an analytical approach to the problem of the development of doubly curved forms and examples related to the definition of 3-D form of garments. Approximations are used to reduce the complexity of patterns and strategies are proposed to optimize the design process by user feedback, again using graphic display.

Custom shoe manufacturing has also been described in Lord (1987) and Lord and Travis (1990). The concept is to digitize the foot, model its shape and modify it for manufacturing. It is observed that for optimal fit the surface shape needs higher resolution in the area of high curvature around the heel. An optical scanner is used to capture 1000 x, y, z coordinates from each single view. About 2000 points are taken out of multiple views to reconstruct the entire surface of the foot. One of the features of the modeling process is to allow the user to change the position of the foot to conform to a new heel height. The modeled shape is then modified into an appropriate last shape for manufacturing.

COMPARATIVE MORPHOLOGY

Human Morphology

The study of human morphology has the potential of improving early diagnosis of a large variety of diseases. Such an undertaking requires tools that are not yet widely available. Indeed, to build a database for the interpretation, analysis and classification of normal and abnormal morphological trends will require large-scale studies.

A good review of the evolution of tools for the study of the human morphology can be found in Sheffer and Herron (1989). Subjects treated cover data acquisition, reduction and analysis.

Smith, Jones, and West (1990) describe a new tool in the research of human body composition. In their study they examined the usefulness of the LASS system (Jones et al., 1989) for calculating human body volume and hence density and found it correlated well ($r = 0.97$) to the same measures by underwater weighting.

Lele and Richtsmeier (1991, 1992) proposed a mathematical approach for comparing biological shapes using landmarks. A unique feature of the approach is the fact that it is coordinate-free (Richtsmeier & Lele, 1993). An extension of the method to surface data (using surface curvature) is likely to produce interesting developments. For a further, extensive review on landmark-based morphometry, see Jones et al. (1995). More recently, Jones et al. (1995) describe a data format which can be used for description, averaging and comparison of 3-D body shapes. The same authors describe a mathematical approach to the generation of 3-D body shapes from simple anthropometric measurements (Li & Jones, 1994; Jones et al., 1995).

Biological Shape Variation

Biological shape variation has had little practical importance since methods for rigorous analysis have

significantly lagged development of techniques for surface and volumetric data acquisition and manipulation in the last decade. It has not been possible to efficiently and reliably deal with biological shape variations in clinical medicine. Grenander and Miller (1994) have given us a new set of tools to understand biomedical silhouettes, projection radiographs, serial slices, and volumetric image data sets. Extension to three and four dimensions where shape varies with time, is anticipated.

Growth Studies

Allometric growth was originally defined by D'Arcy Wentworth Thompson in 1942 (Tanner, 1981), where he stated the "regular and systematic pattern of growth such that the mass or size of any organ or part of a body can be expressed in relation to the total mass or size of the entire organism according to the allometric equation y=bxa, where y= the mass of the organ, x= mass of organism, a = growth coefficient of the organ and b = a constant.

Application to populations allows separation of individual differences from normal variation. Grenander and Miller's (1994) work will revolutionize allometry applied to study of normal and abnormal human growth and development, interspecies variation, and sexual dimorphism. Their method provides a mathematically tenable means to isolate markers for testing heritability of traits through quantitative genetic analysis.

Anthropology

Richtsmeier (1989) claims that the study of forms is central to evolutionary research. Three main fields of studies are discussed: growth, speciation and sexual dimorphism. It is also shown that 3-D measurements can monitor shape variations due to dentition and puberty. Research activities are directed at the analysis of normal and abnormal growth in order to predict and diagnose malformations.

Computer tools have been developed to reconstruct human fossils (Kalvin, Dean, Hublin, & Braun, 1992). It is shown, for example, that mirror imaging is very useful for matching and positioning fragments when a set is incomplete. The authors note that geometric modeling and computer visualization provide anthropologists with both quantifiable computer-based generic (CAD) models and physical plastic reconstruction of fossils. Savara, Steen, and Vannier (1985) stress the importance of 3-D imaging in preserving the morphology of fossil specimens. This reduces the problem of lost specimens and makes the data available to researchers throughout the world.

Population Anthropology

Imaging tools for population screening are under development in Japan (Uesugi, 1991). A full-body optical scanner has been integrated in a mobile unit. The system used by the Research Institute of Human Engineering for a Quality Life will collect data on 50,000 Japanese subjects. Data will be used to revise Japan's industrial standards and other manufacturing guidelines.

Similar studies are already being carried out by the Human Measurements Anthropometry and Growth (HUMAG) Research Group, Loughborough University, where to-date a data-bank of over 300 people have been scanned on the LASS system together with appropriate anthropometric measurements. The 3-D data are being interrogated for use in the clothing manufacturing industries and medical applications (Jones et al., 1993-1994). The reliability and repeatability of 3-D whole-body scanning measurements and anthropometry are reported by Brooke-Wavell et al. (1994).

Human Motion Analysis

Dynamic studies have been done since the invention of photography more than 100 years ago, but it is only recently that such studies have used 3-D measurements. In Allard, Nagata, Duhaime, Labelle, and Murphy (1985) the dynamic characteristics of the ankle are studied using stereophotogrammetry and mathematical modeling. Accuracy of 0.4 mm is reported.

Human motion analysis has also proved useful to plan intra- and extra-vehicular space activities (Probe, 1989). Stereovideo sequences are analyzed to extract 3-D coordinates of joint centers. The digitized sequence provides joint velocities and accelerations. Tests are done in a one-gravity laboratory environment, in neutral buoyancy, and in zero gravity on board a KC-135 jet. It is interesting to note work on 3-D measurements of body and limb volume changes during extended space missions. Using Photogrammetry, these changes were reported as

early as 1970 (Herron, Cuzzi, Bender, & Hugg, 1970).

Forensic Imaging

Amongst the most fundamental human abilities is face recognition. This aptitude is used frequently for criminal investigation and suspect or victim identification. Nagamine, Uemura, and Masuda (1992) report a 3-D imaging approach for automatic matching of the human face using horizontal, vertical and circular sections. Three-dimensional data images of 256 pixels x 240 pixels are obtained by a laser range finder at a resolution of 1 mm. In Russell (1990) faces of missing children are computer aged in order to facilitate recognition. Although the process involves 2-D imaging, it is noted that an ideal system should allow the possibility of rotating images, a feature that 3-D imaging provides.

In a paper by Vanezis et al. (1989) 3-D facial or skull reconstruction are realized. Two techniques are compared: a sculpting technique using clay and a 3-D computer graphics technique using a laser digitizer to input the skull shape within the computer environment. In this research, the authors want to reconstruct the appearance of a subject from an unidentified skull. Conclusions are that computer reconstruction has the advantage of allowing the generation of several faces compatible with the underlying skull and that one of the present limitations is the lack of detailed facial thickness measurements. Facial expression syntheses is also foreseen to be very important for identification.

Hearing Studies

Decraemer, Dirckx, and Funnell (1991) report the use of 3-D imaging techniques to study the human tympanic membrane, especially the coupling of acoustic sound pressure in the external ear canal to the motion of the middle ear ossicle. This work is particularly interesting for the modeling techniques used in the analysis of physical properties. The same approach could be applied to a variety of other dynamic studies related to human motion. Resolutions reported are in the order of 40 μm along the x and y axes and 5 μm along the z axis.

VIRTUAL REALITY AND COMMUNICATIONS

This recent field of research is developing very rapidly and receiving considerable attention. It is based for the moment, on synthetic images for generating 3-D virtual environments. More recently, the integration of photographic 2-D images which are mapped on the synthetic scenes in order to improve realism have emerged. It is most likely, though, that such approaches will evolve to integrate not only photographs, but also 3-D scanned scenes, objects and people, as the technology progresses.

Telepresence

This type of application is where the user needs to be surrounded by a remote environment. Typically, a visual input is provided to users, allowing them to interact remotely with various tools, including the visual sensor parameters such as the direction of viewing and the field of view.

An elaborate system (Drascic & Grodski, 1993; Milgram, Drascic, & Grodski, 1991) has been developed to provide the user not only a stereoscopic view of the scene (two video camera input) but also the means to take precise measurements using a remotely controlled laser pointing device. Relative positions of objects are obtained through stereoscopic vision, while absolute measurements can be achieved for specified geometric features. The relationships between the manipulator-to-camera and the operator's hand-to-eye position is also being studied. The resulting observations show that different viewing conditions affect the performance of different aspects of the teleoperator's task. It is also observed that stereoscopic display significantly reduces task time.

Three-dimensional Portraits

The 3-D reproduction of the human face and body dates back to more than a century ago, but it is only in the last century that artists and engineers have attempted to mechanize the process. One of these processes, known as Photo Sculpture (Grindon, 1989), drew a lot of attention. The technique, invented by Francois Willéme in 1860, is reported by Newhall (1958) to replicate the human form by using 24 cameras to take pictures all around the subject. The physical reproduction process was based on projections of individual photographs and the use of

a pantograph to 'sculpt' a piece of clay. Studios opened in Paris, London and New York and were in operation between 1863 to 1867. Unfortunately, the process was found to be no more easy or economical than the traditional way of making sculptures and was eventually abandoned.

With the advent of computers and electronic cameras, the process regained interest in the 1980's. Cyberware developed a 360° rotating laser profiling system (Addleman & Addleman, 1985) and computer controlled milling for the reproduction of the head and bust. The system has also been successfully used for special effects in motion pictures.

Vision 3-D in France has pioneered a similar digitizing arrangement using laser beam profiling and Cencit (Grindon, 1989) developed a multi-camera incoherent light projection system reminiscent of the early work of Willéme. Posing times were in the order of a few minutes in the 1860's, they are now in the order of seconds for a resolution of typically 1 mm. It is interesting to note that the process still requires substantial human interaction for styling and finishing.

Computer Animation of Human Models

Visual communications are dominated by the visualization of human face movements and expressions. Researchers in this field of activity are developing computer graphic tools for the synthesis of expressive faces (Waters & Terzopoulos, 1992; Terzopoulos & Waters, 1990a, 1990b; Carignan, Yang, Magnenat Thalmann, & Thalmann, 1992). Applications range from low bandwidth teleconferencing, synthetic speaker and actor and human behavior simulation.

Realism is increasing rapidly as the process is refined. Typically, a physical model is created. It contains parameters for the definition of the physical and geometrical properties of skin and muscles. The physical model is deformable (Lee, Terzopoulos, & Waters, 1993) so it can be adapted to a 3-D digital image (including color texture) of a real individual. In Williams (1990a, 1990b), software tools are developed for digital editing and painting of 3-D images. The aim of this research is to create consistent unified methods for computer- assisted drawing, painting, modeling and animation for artists.

Mase and co-workers (1987, 1990) describe a real-time head motion detection system for various man-machine interactions, such as virtual environment feedback and medical aids for disabled persons. The NTT Human Interface Laboratories and the ATR (Advanced Telecommunications Research Institute) in Japan are developing 2-D and 3-D facial image processing techniques for visual telecommunications (Zheng & Kishino, 1992; Delingette, Watanabe, & Suenaga, 1993). Various deformable physically based models and digitizing techniques are proposed (Advanced Telecommunications Research Institute International, 1992).

ISSUES

Spatial Definition Requirements

The above review of applications of digital imaging of the human body shows clearly that spatial definition requirements are mainly related to the size of the body segments to be digitized. Scanning the shape of the cornea or the surface of a tooth necessitates sampling densities much higher than the surface of the trunk or of a leg.

Because most body segments are fairly smooth and regular in shape, we can expect that changes in surface normals are the best way to specify spatial definitions. Essentially this means that each body segment (defined in its simplest form) needs approximately the same number of samples to define its shape. As an example, a finger segment would require for its definition about the same number of samples as a leg segment or an arm segment. On the other hand, one can expect to need a higher number of samples if the head is considered as a unique segment. This is due to the very different topology of the surface of the human face as compared to other body segments.

Limitations of Human Subjects

The human body is a living organism in constant motion. It is subjected to variations in shape from external (gravity) and internal factors. Shape variations of a subject are induced by changes in facial expression, sway, respiration, body fluid distribution, shifts in pose, pulsation of the blood and motor reflex correction for control of postural stability. Occlusion is another limitation imposed by the complexity of whole-body topology and the large number of degrees of freedom of its segments.

Skin pigmentation and scattering properties also limit the accuracy of measurement. Because the human skin is quite transparent (especially in the red portion of the visible spectrum), most optical sensing techniques will underestimate skin elevation. Studies of optical propagation in biological tissues can be found in Grossweiner, Karagiannes, Johnson, and Zhang (1990), Arnfield, Tulip, and McPhee, (1988), Yoon, Welch, Motamedi, and van Gemert (1987), and Bolin, Preuss, Taylor, and Sandu (1987).

Last but not least, hair interference is likely to be the most difficult challenge in automating body surface anthropometric measurements. The distribution and density of hair is difficult to predict, dark pigmentation demands very high dynamic range optical sensing and sampling density requirements for shape description are much too coarse to allow its resolution.

Camera Limitations

Speed is presently one of the most limiting factors for human body imaging. Few approaches are able to digitize the full body at a resolution appropriate for anthropometric studies. Typically, the acquisition time is more than 10 seconds, which is long enough to be susceptible to most of the subject's shape variations mentioned above.

Portable devices would be ideal, especially for large population database collection, but with the exception of the Nippon Koukan Kabushi higaisha (NKK) mobile unit (Electronics Research Center, 1993), there is no easy way to transport most of the full body 3-D imaging systems described in this review.

Laser-based systems have the advantage of depth of field, but they pose eye hazards, which necessitate either protection or proper camera design. For a brief review of laser radiation hazards see Henderson (1984). Eye-safety is achievable if the laser wavelength is selected in the 1.5 μm range (Rioux, Beraldin, O'Sullivan, & Cournoyer, 1991), but the costs associated with the laser source and the optical sensing element are presently prohibitive.

Generally speaking, the technology available to digitize the human body is complex to operate, necessitates careful calibration, and requires well-trained operators to maintain performance.

CONCLUSIONS

From the survey of applications related to the measurement of the human body we find that at least three levels of resolution are needed: high resolution (10-100 μm) for shapes in the size range of teeth, medium resolution (100 μm-1 mm) for the face, hand and foot and low resolution (1-5 mm) for the trunk and limbs.

Many researchers complain about the lack of a database of normal and abnormal human shape measurements; this lack is seen as an impediment to the development of applications. From various sources, it is estimated that traditional anthropometric measurements cost between $50 and $500 per subject, depending on various factors such as the number of parameters measured, the number of sites visited, the constraint on time and the sample size. There is no need to explain why large scale-surveys are almost non-existent. Databases are sometimes collected by people having very little training in the proper use of the equipment and appropriate research methods. In some cases improper equipment is used, impairing the reliability of the data collected. It has been also documented that there are large inter- and intra-observer variations between anthropometrists (Fowkes & Aiken, 1990) when taking traditional measurements. A cost analysis using surface imaging may be appropriate at this time. We must establish it for the size of the sample and also for the number of parameters to be collected and interrogated. With a fully automated system, it may be more cost effective to measure thousands of individuals rather than hundreds.

We also find that some applications require only a single view recording, such as in the study of the back in spinal disorders, in the fitting of face masks and in a number of prosthetic interface fittings. However, most applications would benefit from multiple views with a minimum of a front and a back view. For more surface coverage, three or more views may be needed. Moreover, it is clear that no current surface imaging system will be able to digitize 100% of the body's surface, especially in cases where the user wants to make recordings with the subject in different postures. The human shape is too complex and possesses too many degrees of freedom to devise a practical 100% surface collection digitizing system.

Nevertheless, it is abundantly clear that 3-D imaging can produce useful information, extending way beyond that which can be derived using earlier simple anthropometric techniques, for a multitude of differing applications.

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CHAPTER III: DATA COLLECTION

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INTRODUCTION

State-of-the-art digitizing technology is being used in many fields to improve the performance and quality of anthropometric related activities. For the most part, technology has not changed the basic objectives of anthropometric evaluations, but it has definitely changed the methodologies used to accomplish them.

For some time photographic methods have been available to speed up the data collection process, but it is only with the advent of computers and digital sampling that selected points could be extracted from electronic images. At first, targets were attached to the selected feature points on the human body and photographs were digitized, now electronic cameras are used to supply the information directly to the computer for processing. Use of video cameras has also allowed the study of the dynamics and the mechanical properties of the moving body.

However, the selected points collection approach is limited in geometric description capability, and the future of anthropometric data collection is likely in the direction of an exhaustive surface sampling approach (imaging) where millions of points are digitized and analyzed. The resulting file is a set of geometric function parameters or, in other words, an equation of the human body geography.

Data collection methods are generally separated into those whose principal application requires the description of surface details and those that require internal (volume) details. Most of the surface imaging methods use non-penetrating energy, such as laser light, to provide range information on surface morphology. Volumetric imaging systems use penetrating energy, such as electromagnetic radiation or sound waves, to gather information on internal structures.

This chapter will briefly review available data collection techniques developed and also those presently under development, both imaging and non-imaging arrangements. Their limitations, such as imaging issues related to hair interference, occlusions, subject motion during recording, and exposure risks to laser and ionizing radiations, will be discussed.

Traditional Methods

The measuring tools for "traditional" anthropometry include calipers, tape measures, anthropometers, and measuring boxes. Measuring boxes are containers in which the sides, walls, or other box surfaces function as a surface against which measures are made. Figure 3-1, taken from Webb Associates (1978), illustrates some of the different types of traditional measurements.

Advantages

For simple applications, traditional anthropometry methods are both inexpensive and fast. For example, to select a shoe size for a customer a simple caliper type measure of foot length and ball of foot width is very efficient.

Traditional tools can be used effectively to measure areas that are not visually accessible, such as the clearance distance in a cockpit (Figure 3-2) or the inside of the arm (Figure 3-3).

Another advantage to traditional anthropometric methods is the widespread availability of the tools. These methods are accessible to groups who cannot afford some of the more expensive technologies.

Limitations

As discussed in the Introduction, there are several problems in using traditional anthropometry. Ambiguous contours can be derived from the same set of measurements, the orientation of body segments has an impact on the measurements, data may not be available to support product design, and there can be large differences between observers who collect the data.

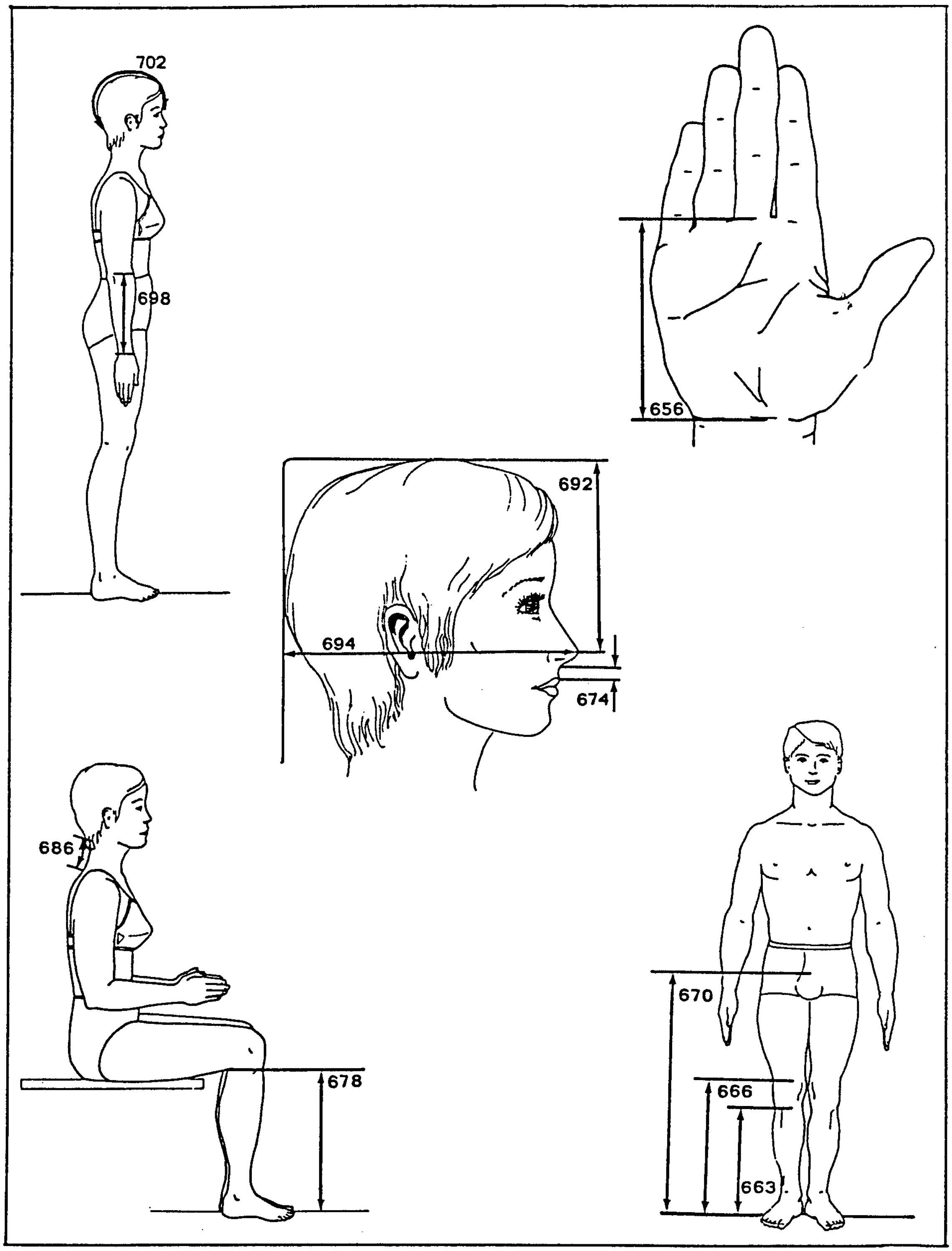
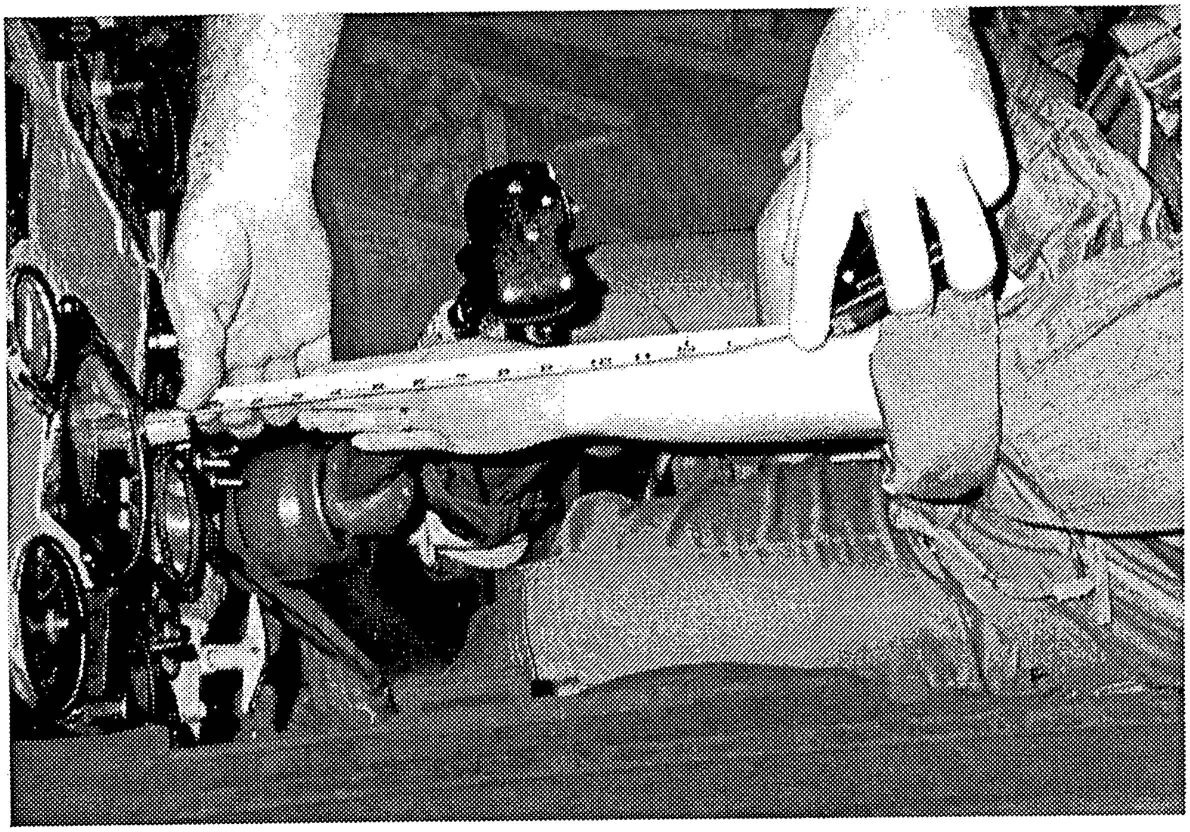


Figure 3-1. A selection of traditional anthropometric measurements (from Webb Associates, 1978).

Reach to Controls



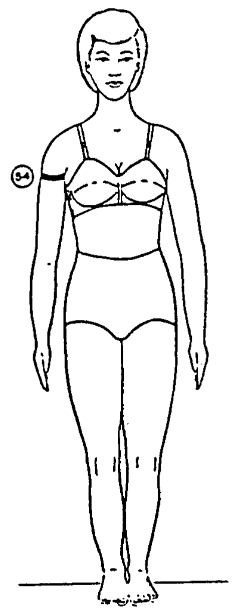
Variability Not Only from Arm Length. Other Factors Include:

- Seat Position
- Shoulder Height
- Shoulder Width
- Restraint System
- Motivation

Figure 3-2. Measuring reach in a cockpit.

(54) AXILLARY ARM CIRCUMFERENCE

Subject stands with right arm abducted sufficiently to allow clearance of a tape between the arm and trunk. With a tape held in a plane perpendicular to the long axis of the upper arm, measure the circumference of the arm at the level of the anterior arm-scye landmark. The axillary tissue is not compressed.



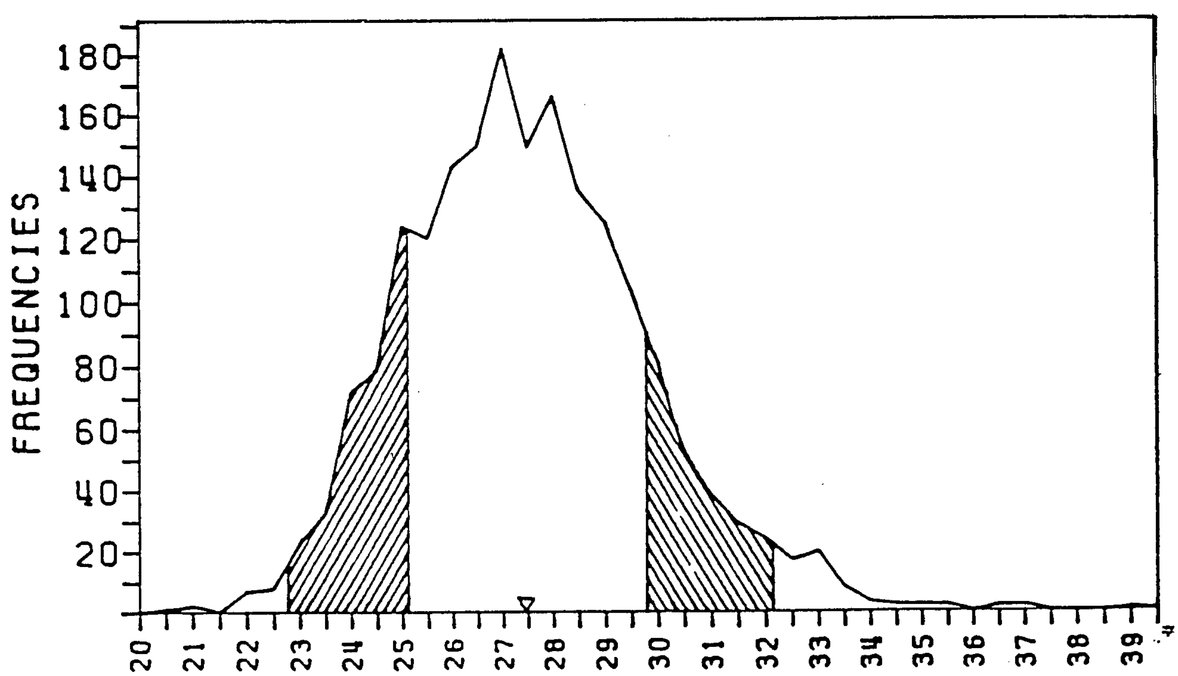


Figure 3-3. Axillary arm circumference measurement extends under arm (from Churchill et al., 1977).

Photography

As mentioned in the Applications chapter, there is a long history of photographic means to record the human shape. The Photo Sculpture process (Newhall, 1958) is in fact a silhouette recording arrangement, where 24 cameras provide 24 profiles of the subject. A similar approach is taken by Quattracolo and Holzer (1992) to record orthogonal profiles of a subject in an application concerning custom clothing fabrication.

Film-based systems have been used for about a century with extensive visual analysis to interpret and extract the desired information. The most popular approach is stereo pair recording. In this arrangement two photographs are taken from two different points of view and placed in a specialized stereoscope for coordinate measurements.

Photogrammetry

The stereo pair approach has led to the development of the field of photogrammetry where images are analyzed by computers to extract three-dimensional coordinates. There are two basic arrangements, i.e., with and without targets. In the early 1970s Herron (1972) published a report on the measurement of body forms using biostereometry. Pinkney et al. (1978, 1986) also developed a real-time video photogrammetry system for the tracking of known geometry multiple targets using a single video camera. It allowed a 30 Hz measurement rate for three-dimensional machine control task. Such photogrammetric techniques have been used by Jensen (1978) for the study of biomechanical properties of the human body.

In El-Hakim (1986, 1989) the geometry of the target array is not needed. A two-camera system is used to extract individual target 3-D coordinates. It is a stereo vision arrangement that has been generalized to multiple camera geometry, for improved performance (El-Hakim & Pizzi, 1993).

An excellent review of photogrammetry, covering the historic evolution of the field, the basic concepts, and a variety of applications, can be found in Karara (1989). Essentially, in photogrammetry, one or more photographs (or views) are used to extract 3-D coordinates of a scene. Applications of photogrammetry were mainly for the production of topographic and other maps of terrain. Today it is also used for a large variety of industrial and medical applications.

For medical diagnostics, a ten year series of bi-annual conferences on surface topography, spinal, and body deformities has reported progress in the field of photogrammetry to record, analyze, and propose procedures for the early diagnosis of various types of body structure anomalies.

Photogrammetric techniques have also been used in X-ray imaging where stereo pairs are used to visualize or localize anatomical features in three dimensions. Piccaro and Toker (1993) have developed such an arrangement, a CCD-based digital imaging system for mammography. Two stereo X-ray images are used to achieve stereotactic localization of breast lesions.

Videography

The target approach has also been used to achieve reliable and inexpensive means of motion sequence sampling. Systems have been built and are commercially used for gait and motion analysis. Costigan et al. (1992) use an optoelectronic system (Watsmart) that tracks active infra-red emitting markers to study knee motion. The system consist of two video cameras with about 75 degrees separation and positioned 6 meters from the walkway. Previously, Schaer et al. (1985) used 16 mm cameras to record the stereo data in a similar study of human knee joint movements during walking.

In all cases, the approach requires the use of markers and at least two motion recording cameras. Each frame of the recording is analyzed to extract and identify the markers. The 3-D coordinates are computed and interpolation between frames is used to compute the time domain trajectory in 3-D space. The user of such triangulation arrangements must compromise measurement resolution with field of view. The parameters for adjustments consist of the angular separation between the cameras, the camera focal lengths and the distances from the test site to the cameras.

Surface Scanning

Most techniques described up to now are very good at providing 3-D coordinates of specific points on the human body surface but are poor in providing surface shape geometry. Only sparse 3-D data are

extracted from 2-D images. On the other hand, the following techniques can be classified as 3-D imaging recording processes, where 3-D coordinates are densely sampled to form an electronic version of binocular vision. The resulting image consists of millions of coordinates (surfacic or volumetric) that record a detailed electronic 3-D replica of the subject under observation.

Jarvis (1983) and Besl (1988), among others, have completed broad surveys of 3-D or range-imaging methods. These surveys include details on sensing methods, available sensors, and representative performance specifications for these devices.

Optical sensors use a variety of methods to collect 3-D coordinate data from object surfaces. These methods are divided into those that observe on the axis of illumination and those that observe off the axis.

On-axis devices

Several species of mammals, including bats and porpoises, use sound waves to determine their distance from objects (Griffin, 1958; Kellog, 1961). In much the same way, the time required for a radio wave to reflect from a distant object to a receiver is used to determine the distance from the object to the receiver. These systems make use of time of flight to determine the distance from the object to the receiver.

Several time-of-flight imaging laser radars have been developed. For example, Lewis and Johnston (1977) developed an imaging laser radar for the Mars rover that compiled 64 X 64 range images in 40 sec. Several airborne surveying systems are available commercially. One system measures water depths to 40 m with an accuracy of 0.3 m (Banic et al., 1987), while another provides up to 2000 readings per second with an accuracy of 1 cm at a typical 10 to 500 m range (Optech Systems Corporation, 1991).

A variation on the time-of-flight imaging radar uses an amplitude modulated (AM) laser. The range is computed by detecting the phase shift between the transmitted and received signal. Amplitude modulated lasers have been built for research programs and several are available commercially (Binger & Harris 1987; Svetkoff, 1986). The Perkin-Elmer airborne laser radar scans 2790 pixels per scan line in 2 ms. The forward motion of the scan line is provided by the aircraft motion (Keyes, 1986).

Another method of image ranging can be provided by varying the optical frequency of the laser (frequency modulation (FM)). The reflected return signal is mixed with the reference signal at the detector. The beat frequency that is created depends on the range of the object (Skolnick, 1962). This detection process is termed FM coherent heterodyne detection. Two commercially available FM imaging laser radars are reported by Hersman et al. (1987).

The surface characteristics and range of an object also can be determined by focusing the image of the object (Jarvis, 1976; Krotkov & Martin, 1986). Paradoxically, the autofocus mechanisms in cameras frequently use other methods of ranging. For example, the Canon "Sure-Shot" autofocusing mechanism is an active triangulation system using a frequency modulated infrared beam (Jarvis, 1982).

Shape from shading

Humans perceive shapes not only from binocular vision but also from light variations scattered from objects and scenes. This is why a photograph is easily interpreted by humans and, although ambiguities exist, most of the photographic subjects are reconstructed as 3-D shapes. Attempts to duplicate this process fall under the shape from shading technique. The objective is to recover shape information from illumination and object scattering models. A variation of this approach is described in Laurendeau et al. (1991). A dental imprint is submerged in a liquid that has known absorption coefficients at the wavelengths of illumination. The amount of light intensity measured by a CCD camera is proportional to both the elevation of liquid above the surface of the object and the surface orientation. Image processing of the resulting images allow recovery of 3-D coordinates of the imprint shape.

Off-axis devices

Triangulation uses the law of sines to measure the distance to a remote object. An example of an active triangulation system is shown in Figure 3-4.

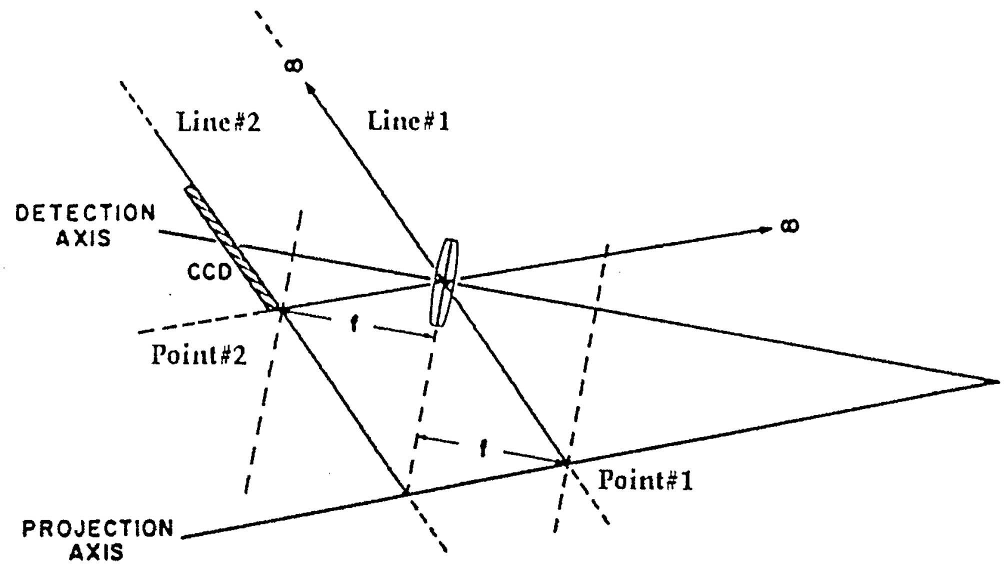


Figure 3-4. Construction of the triangulation geometry with the Scheimpflug condition.

A beam of light is projected along the projection axis to a remote object. The surface of the object scatters light in all directions. The part that is directed along the detection axis is focused to a position sensitive device, typically a CCD (charge coupled device) composed of a linear or an array of pixels. The distance is measured using the position of the illuminated pixels. When an object is closer than the intersection of the projection and the detection axes, the illuminated pixels move away from point #2. Conversely, when an object is farther than the intersection, the illuminated pixels are closer to point #2. A unique property of an off-axis geometry is that defocusing with range can be easily compensated using the well known Scheimpflug condition. The geometric construction is illustrated.

The structured light that is projected onto the object can be focused to a point or a line. Point scanning systems will project the light in a horizontal and vertical range to create a composite image of the scene. Commercially available spot scanning systems project white or laser light to detect range information (Cyberoptics, 1987; Gottwald & Berner, 1987; Selcom, 1987).

Passing a laser through a cylindrical lens creates a line of light. The light stripe changes shape as it traverses the surface of a three-dimensional object. Changes in line shape are detected for successive images to determine the 3-D shape of an object. Commercially available light stripe scanners are used for industrial applications, scanning human heads, and robot vision systems (Schmitt et al., 1986; Baribeau et al., 1993; Cyberware, 1993; Rioux et al., 1989; Nahas et al., 1990; Blais et al., 1988; Beraldin et al., 1992).

A moiré pattern is an interference pattern created when two gratings with regularly spaced patterns are superimposed on one another (Selcom, 1987; Pirodda, 1982). In moiré range-imaging sensors, surface depth is recovered from the phase difference obtained after the signal is filtered with a low-pass filter. Moiré range-imaging is most useful for measuring the relative distance to surface points on a smooth surface. Commercially available moiré scanners use projected light, shadow, or framing techniques (Electro-Optical Information Systems, 1987; Cline et al., 1984; Halioua et al., 1983; Reid et al., 1986).

Holographic interferometers use coherent light from laser sources to produce interference patterns due to the optical frequency phase differences in different optical paths. Surface depth information is recovered from the phase difference term. Just as in moiré range imaging, the measured surfaces must be smooth and flat. This technology is useful in commercial applications to visualize stress, thermal strain, pressure effects, erosion, microscopic cracks, fluid flow, and other physical effects in nondestructive testing (Tozer et al., 1985; Mader, 1985; Wuerker & Hill, 1985; Church et al., 1985).

Rioux and Blais (1986) developed two structured light techniques using lens focusing properties for ranging. They use a mask in the camera lens to achieve triangulation through the lens. The first technique uses a grid of point sources projected onto the scene and an annular mask. The range to each point is determined by the radius of the annular blur in the focal plane of the camera. In the second arrangement, a multistripe illuminator shines on the scene and a double aperture mask is used. If the stripe is not in focus, the camera sees split lines. The distance between lines is proportional to the distance to the surface.

White light projection (incandescent light) is also used to define surface features for triangulation measurements. In Vannier et al. (1991), a pattern is projected from various orientations in a time-multiplexed sequence and synchronously recorded by a multi-camera assembly. Each camera-projection system supplies a dense 3-D mapping of the subject's head that is integrated with all the other views. The resulting 3-D image describe the subject's size and shape along 360 degrees. The recording time is less than a second.

One other multi-projection, multi-camera system has been built for full body, 360 degree recording of the human figure (Jones et al., 1989). It consists of a projection system that forms four vertical lines of light and a set of video cameras and frame grabbers to digitize a rotating subject. The recording time is in the order of 60 sec., but motion compensation is achieved by processing front and back projection recorded profiles.

A commercial system to digitize the human head is also available from Cyberware (Addelman & Addelman, 1985). A laser line is projected on the subject and the camera is rotated around 360 degrees to capture a 3-D image in about 15 sec. Shadow effects are minimized in a geometry that combines two opposite views on the same camera sensor.

Recent developments in this approach integrate a color image texture to the 3-D data. This is done by a second color CCD camera that digitizes color information and registers it to the 3-D file.

At the NRC laboratories, a demonstration of full body recordings has been done using a synchronized laser scanner (Nahas et al., 1990). An infrared laser is scanned vertically to measure profiles while the subject is rotating continuously over 360 degrees. In a second mode of operation, multiple raster scans are made at intervals of 90 degrees. The recording time is about 30 sec per image.

The basic geometric analysis of the synchronized scanning can be found in Rioux (1984). A laser beam projection system using a scanning mirror is synchronized with a position sensing system using the back facet of the same scanning mirror. Further analysis of this geometry is in Rioux et al. (1987), where diffraction limitations are given for optical system design purposes. It is shown that resolution in 3-D is related to the wavelength of the laser light and that optimal performances are obtained when the Scheimpflug condition is applied to the detection system.

A prototype based on the synchronized scanning geometry is illustrated in Figure 3-5. It is mounted on a photographic tripod and, in this photograph the camera is moving vertically while the profiles are digitized horizontally. The results of the scans are displayed in Figure 3-6.

A high-speed polygon version of the synchronized scanner has also been used to demonstrate an eye-safe approach to laser 3-D digitizing (Rioux et al., 1991). A 1.5 m laser is used for the projection and a custom-made position sensor for detection. The main advantage of using 1.5 m is that this wavelength does not penetrate the cornea, thus preventing focusing of the laser light to the retina. A substantial increase in laser power can then be used. This makes it possible to increase measurement resolution and data acquisition speed.

Contact devices

Tactile methods still dominate most applications where the exact shape of a prototype object must be duplicated. However, coordinate measuring machines inherently are slow and expensive. Optical non-contact imaging methods will produce a cost savings if they are fast, accurate, reliable, and easy to use (Besl, 1988).

However, some recent developments in single point measurement allow the user to digitize 3-D coordinates of the human body. The concept lies in a probe that is emitting a light, an electromagnetic, or an acoustic signal, which is detected by three or more sensors. The probe is generally on the tip of a stick and manually positioned to the surface feature the user wants to digitize. Although the resolution of such devices is acceptable for anthropometric data collection, the data acquisition speed is extremely slow. If a surface has to be digitized, the subject under measurement must stay immobile for tens of minutes. The resulting file still consists of only a few hundred points at best.

One way to improve stability and data acquisition speed for anthropometric applications is to devise a special support structure (Annis & Gordon, 1988). In such an arrangement. the subject is kept stationary relative to the measuring instrument. This has been demonstrated for head and face measurements. For the full body though, it would be very difficult to implement because of the large number of degrees of freedom of all the body segments.

Volume Scanning

Volumetric imaging of the human body has leapt forward with demands for improved images as diagnostic tools in medicine. Most diagnostic imaging is done in the radiology department and is segregated into five categories: ultrasound imaging, X-ray computed tomography, magnetic resonance imaging, nuclear scintigraphy (including PET and SPECT), and conventional projection radiography. These imaging modalities provide details on internal structures and usually are viewed with transparent film hardcopy on a fluorescent back light box in a two-dimensional format. However, advances in computer processing of volume data and enhanced tools to present three-dimensional scenes guarantee an increased demand for three-dimensional rendering of these images (Huang et al., 1990; deGuise & Roberge, 1989).

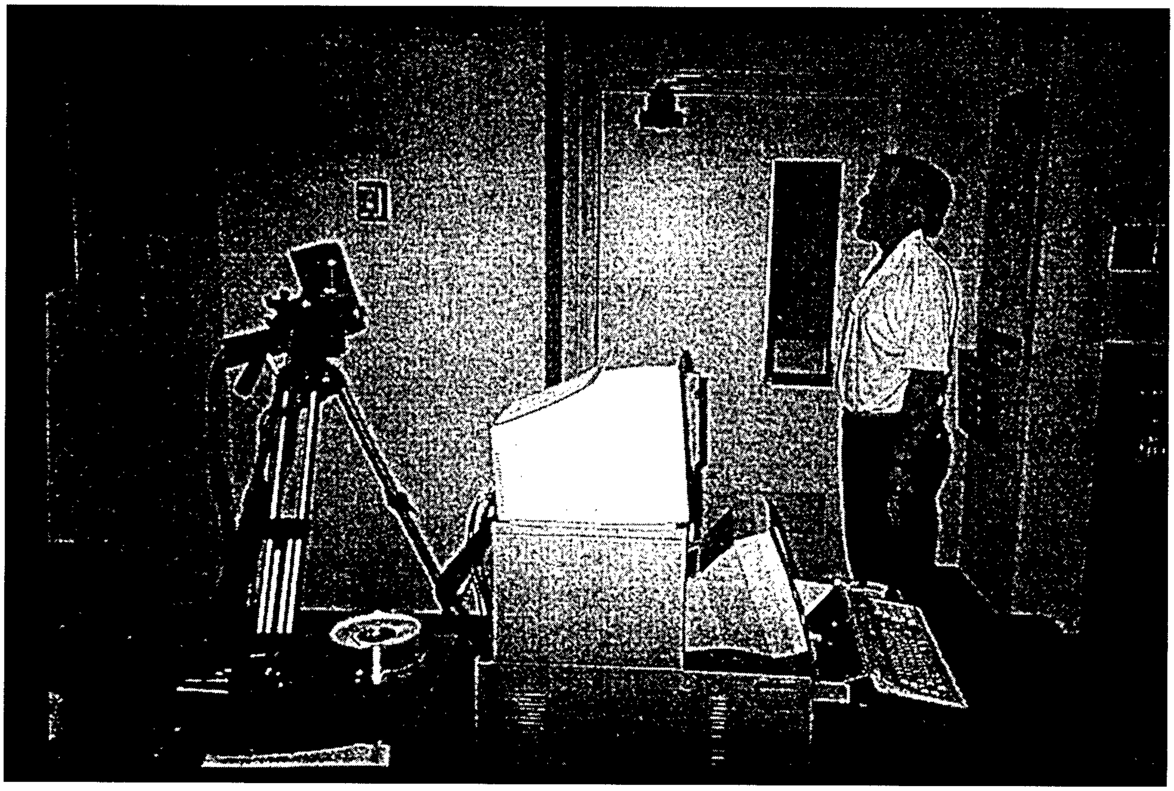


Figure 3-5. A synchronized scanner prototype mounted on a photographic tripod. The laser scan is horizontal while the camera rotates vertically.

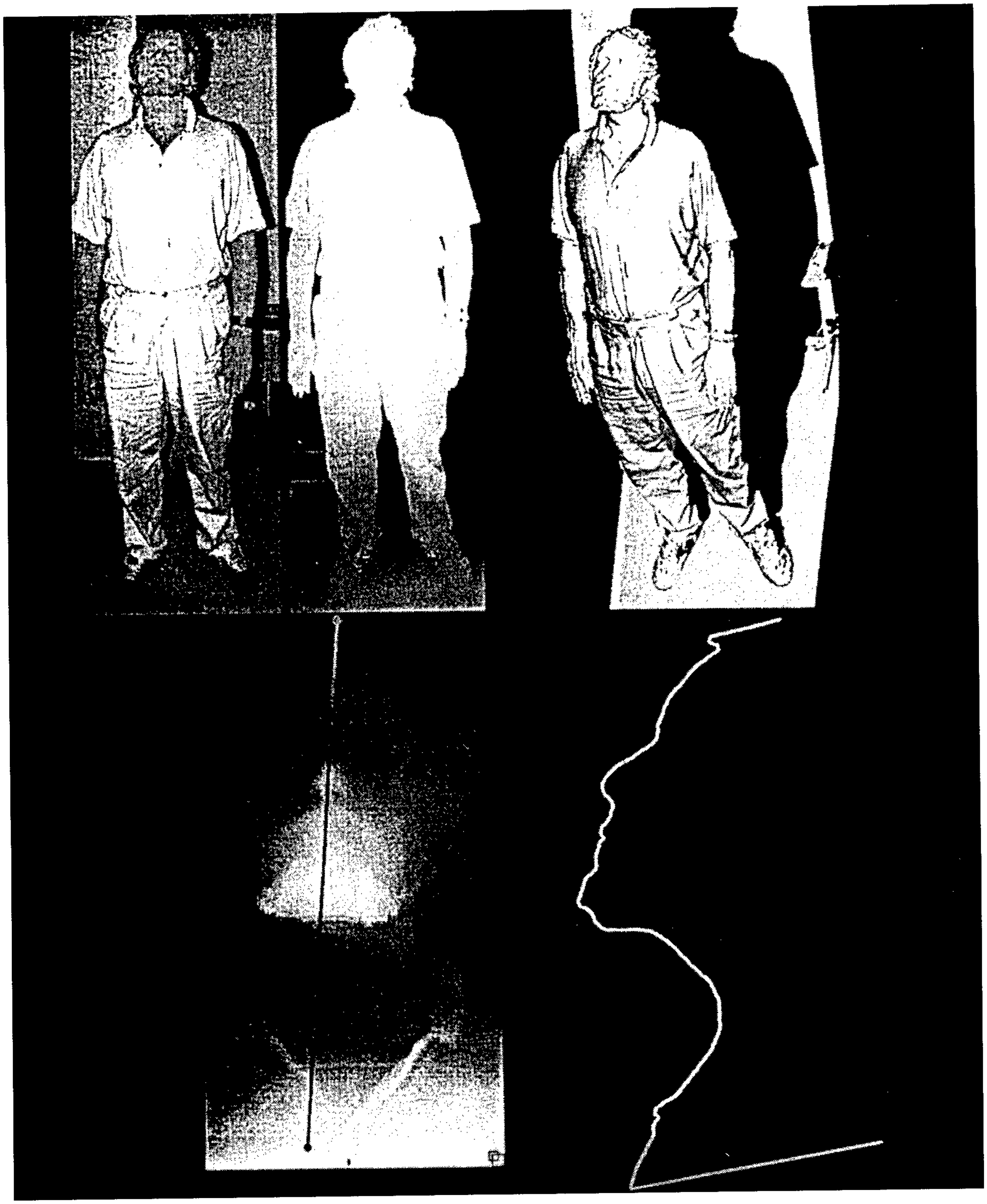


Figure 3-6. Results of a surface scan, top left: the intensity file, top center; the 3-D file, top right; surface rendering using a graphic workstation, bottom left: a zoom in the 3-D file with a measurement line, bottom right; the profile along the measurement line.

X-ray Computed Tomography (CT)

In a conventional radiograph, transmitted X-rays form a composite image of the internal structure of the body. The amount of radiation that passes through the body is inversely proportional to the density (radiopacity or attenuation and scatter) of the tissues. Plain radiographs provide excellent spatial resolution, but soft tissue discrimination is relatively poor and overlapping structures can obscure details (Vannier & Marsh, 1992).

The X-ray computed tomography was introduced in the 1970 s and the 1979 Nobel Prize for Medicine was awarded to Cormack and Hounsfeld for this development (Cormack, 1963; Hounsfield, 1973). In computer-assisted tomographic scanners, multiple radiosensitive detectors view a moving X-ray source. The computer reconstructs the data into slice images. From early units with a low resolution and 1.5 cm slice thickness have emerged current high-resolution CT scanners. With the high-resolution technique, a 512 x 512 reconstruction and display matrix can be concentrated in a small region of the skull and slice thickness can be reduced to 1 or 2 mm (Vannier & Marsh, 1992). High-resolution CT is used widely in clinical medicine, particularly when evaluating masses in the head, chest, and abdomen (Huang et al., 1990). Spiral CT scanning was recently introduced to acquire volumetric data sets.

CT images provide excellent bony details and soft tissue features, but to gain a three-dimensional appreciation of an object, the observer must mentally integrate numerous sequential two-dimensional images. This interpolation is facilitated somewhat when the two-dimensional images are parallel and equidistant. Computer software has been developed to allow reformation of the CT data to reconstruct a model of the internal details. The reconstruction of axial images are often displayed in rotational projections of three-dimensional structures (Marsh et al., 1986; Vannier & Marsh, 1992).
Three-dimensional reconstruction algorithms have been described (Robb, 1985) and usually adopt one of two strategies:

1. Surface: Two-dimensional contours are extracted from each image. The contours are stacked and geometric interpolation is used to produce the three-dimensional object surface (Batninzky et al., 1981; Christiansen & Sederberg, 1978).

2. Volume: A three-dimensional array of CT numbers is created from the series of tomograms. Each pixel generates a volume element or "voxel" reflecting the thickness of each tomogram slice (Herman & Lui, 1977).

There are two principal methods for displaying three-dimensional information generated in this manner. These are the indirect projection mode and direct three-dimensional mode. In the indirect approach, the three-dimensional object is projected onto an image plane from a given point of view. Depth is added to the scene by brightness coding, simulated light sources, texturing, or continuous rotation of the object. Direct three-dimensional representation requires special hardware, such as varifocal mirrors (Harris et al., 1986) or multiplex holography (Fujioka, 1988). The use of direct 3-D is infrequent in practice, owing to the physical limitations of the viewing apparatus.

Since CT and MR scanners are computer based, it is possible to perform the 3-D imaging on the scanner and avoid the cost of additional hardware. Nevertheless, a stand-alone three-dimensional imaging system may be preferred to avoid interfering with the usage of the scanner. The length of time required to generate a three-dimensional image from the scanner data may be only a few seconds for a specially designed hardware and software system to a few minutes for on-the-scanner software. Of particular concern in this case is whether the three-dimensional image is required for direct interaction or for later review (Herman & Lui, 1977).

Magnetic Resonance Imaging (MRI)

More recent than computerized tomography, magnetic resonance (MR) makes use of proton distribution within biological tissues to produce images of internal structures. The relatively high density of mobile H+ ions in body tissues allow detectable nuclear magnetic resonance signals to be induced. To measure the MR signal emitted from nuclei, such as hydrogen, sodium-23, phosphorus-31, and carbon-13, an applied magnetic field and a second on-and-off magnetic field are used in synchrony with the frequency of the nucleon measured. The detected MR signal is radio frequency (RF) pulses. The location of the MR signal in the electromagnetic spectrum is shown in Figure 3-7.

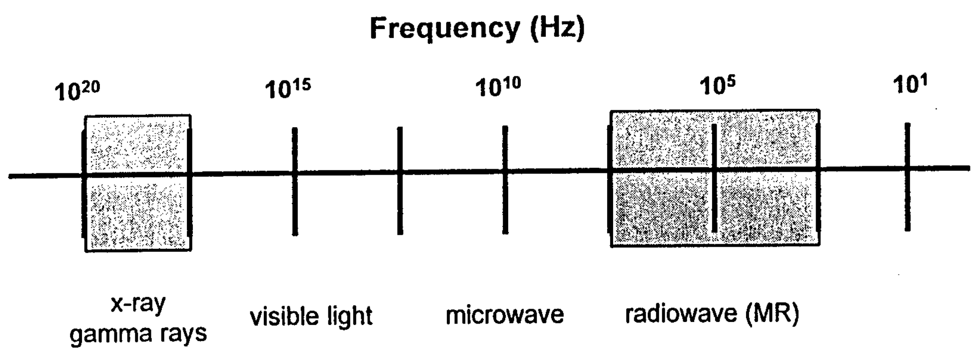


Figure 3-7. Location of the MR signal in the electromagnetic spectrum.

RF stimulation adds energy to the system and causes protons to move to a higher energy state. Dissipation of this energy and return of the protons to the lower energy state is known as T1 relaxation. T2 relaxation results from dephasing of spins as an effect of local magnetic field in homogenities due to randomly varying intrinsic magnetic fields created by adjacent nuclei. The MR contrast effects, including T1 or T2 relaxation times, flow, spin density, chemical shift, magnetic susceptibility, or other factors, manifest themselves as signals detected by the RF coil (Huang et al., 1990; Smith & McCarty, 1992).

After application of excitatory RF pulses, the amplitude of the MR signal decays to zero. This causes detectable signal losses in the sample due to T1 and T2 relaxation effects. The relaxation rates depend on the composition and local environment of the protons in the sample. In other words, the relaxation effects indicate the chemical structures in the local environment. Image contrast is based on the difference in signal intensity between areas of different structure or composition. Superior soft tissue contrast resolution is one of the greatest advantages of MR imaging over computed tomography (Edelstein et al., 1983; Hendrick et al., 1984).

The strengths of magnetic resonance imaging include its lack of ionizing radiation and its sensitivity to flow. This is particularly useful for patients requiring multiple examinations, pediatric patients, and pregnant patients. In computed tomography, the scan plane is defined by the X-ray tube-detector axis. In MR imaging, the scan plane is defined by the selection of RF frequencies and magnetic field gradients. This makes multiplanar studies possible. Magnetic resonance is weak in the areas of calcium sensitivity, acute hemorrhage, and when pacemakers or other electronic devices interfere (Huang et al., 1990). Since MR imaging is recent, its potential has not been fully exploited and its comparative advantages for three-dimensional object reconstruction remain to be firmly established (deGuise & Roberge, 1989).

Ultrasound

Vascular disease is a very common human affliction. While X-ray angiography, using radiopacque contrast, remains the mainstay in diagnosis of cardiovascular abnormalities, ultrasonic imaging of vascular structures provides important information on anatomic structures and vascular flow. Ultrasound depends on the differential transmission, absorption, scattering and reflection of sound waves from constituent biological materials to provide information on internal structures and blood flow (Huang et al., 1990; Feigenbaum, 1986). The technique is best when imaging soft tissue object surfaces or thin-shelled volumes and is poorly suited to access centrally located areas (deGuise & Roberge, 1989). Combining gray-scale ultrasound imaging of internal structures and Doppler for blood flow results in duplex Doppler with simultaneous imaging of anatomic structures and circulatory physiology. In addition, color displays enhance duplex Doppler by providing color-coded images of blood flow (Huang et al., 1990).

The principal uses for ultrasound imaging in medicine are for the diagnosis of carotid bifurcation disease (Jacobs et al., 1985), evaluation of valvular disease and shunts (Huang et al., 1990), thyroid, testis, and abdominal diagnosis, endourology, and imaging the developing fetus. However, the relatively low cost and noninvasive nature of the test make it useful in evaluating tissue layering and masses anywhere in the body. This is a noninvasive technology that does not expose the subject to ionizing radiation (Marsh et al., 1986).

There are several practical limitations in the use of ultrasound for three-dimensional reconstruction of the human form. First, most ultrasound studies do not use fixed reference points on the body and data acquisition is limited to two dimensions. Interpolation of two-dimensional images to three dimensions is simplified in CT and MRI scans because successive images are parallel and equidistant. This is usually not the case for ultrasound images (deGuise & Roberge, 1989). Second, the quality and form of the images depend on the skill of the operator. Third, the ultrasound probe requires direct contact with the skin. Finally, ultrasound images of structures near the skin surface are readily visualized, but osseous structures or structures within the chest cavity are not. Many soft tissue organs visualized by ultrasound are continuously deformable and consistent 3-D data cannot be easily acquired.

Other imaging methods

After World War II, biomedical science was revolutionized by the introduction of carbon-14 and tritium as radioactive tracers. While these agents have been valuable in laboratory research, their beta emissions could not penetrate the body and be detected by imaging devices. More recently, nuclear magnetic resonance spectroscopy (MRS), single photon emission computed tomography (SPECT), and positron emission tomography (PET) make it possible to examine the structure of the living body in situ through its chemical processes. Nuclear magnetic resonance spectra of molecules containing naturally occurring phosphorus-31 or administered fluorine-19 or carbon-13 make it possible to measure molecular concentrations of important compounds, such as ATP, inorganic phosphorous, and chemical reaction rates in different organs and tissues. PET is based on the use of carbon-11 or fluorine-18 and SPECT is based on iodine-123, technetium 99m, and indium-111. These nuclides emit photons that can be detected and imaged. Abnormal tissue can be defined in terms of variation from normal regional chemistry (Wagner & Conti, 1991).

3-D Anthropometry Requirements

The key factors in the performance of a range-imaging system are the depth of field, range accuracy, pixel rate, range resolution, image size, angular field-of-view, standoff distance, and frame rate. Series of images produced with a NRC range sensor are shown in Figure 3-8. It shows the recording of body topography from fingerprint to large group of people. In each case the sampling interval is given.

A unique geometry for achieving such a variety of scans can not be designed at this time. Rather, it is proposed that 3 basic configurations (A, B, and C) be developed for anthropometric applications. Table 3-1 illustrates such an approach where a fixed file format of 2 Mbytes is selected. Figure 3-9 shows the fundamental limits (Rioux, 1994) imposed by the laws of physics when using laser light projection.

Range of view

There is a need to define technology for digitizing of the human body and body segments in terms of their size. Furthermore, the digitizing system should be reconfigurable in order to accommodate various standard human postures. The maximum volume of view (measurement) should enclose the full body in various configurations. For the average population, a cube of 2 m on a side should be sufficient. The smallest volume of view is likely to be in the digitizing of the human hand. In this case a cube of 30 cm on a side would be required.

Noise and artifacts

The conditions of imaging will vary from one site to another. The 3-D digitizing system must be robust to interferences originating from natural and artificial ambient light. The noise limit must be evaluated for each recording configuration. Typically, an instrument has a specific resolving capability, e.g., one part in ten thousand, and the optical configuration is changed to accommodate the desired field of view. For a small field of view the noise level goes down to the micrometer range. For full body 3-D imaging the noise level is around a millimeter.

Any imaging device produces artifacts. For 3-D digitizers the most common artifact arises when there are sudden changes of reflectivities. During the transition, the position sensing device deviates from the true value position. In some cases this effect is more than one order of magnitude higher than the noise. A typical example of reflectivity change is when the projected light source illuminates a transition between skin and dark hair area. Similar artifacts also occur for a sudden change in elevation values, such as a transition from the chin to the neck area. In all cases, such areas of uncertainties can be detected and the 3-D data eliminated or at least identified as of lower confidence.

Precision and accuracy

Calibration procedures rarely allow one to reach an accuracy close to the precision of measurement. It is imperative, though, that accuracy be well documented for 3-D anthropometric measurements. Indeed, the only way to interpret and compare two sets of data (coming from two distinct digitizers and/or two separate sessions) is to have the full knowledge of the absolute accuracy over the field of view. Otherwise, differences that occur at the analysis stage may originate from calibration residuals. A good analysis and discussion of this subject can be found in Beraldin and co-workers (1992, 1993), El-Hakim (1989) and El-Hakim and Pizzi (1993).

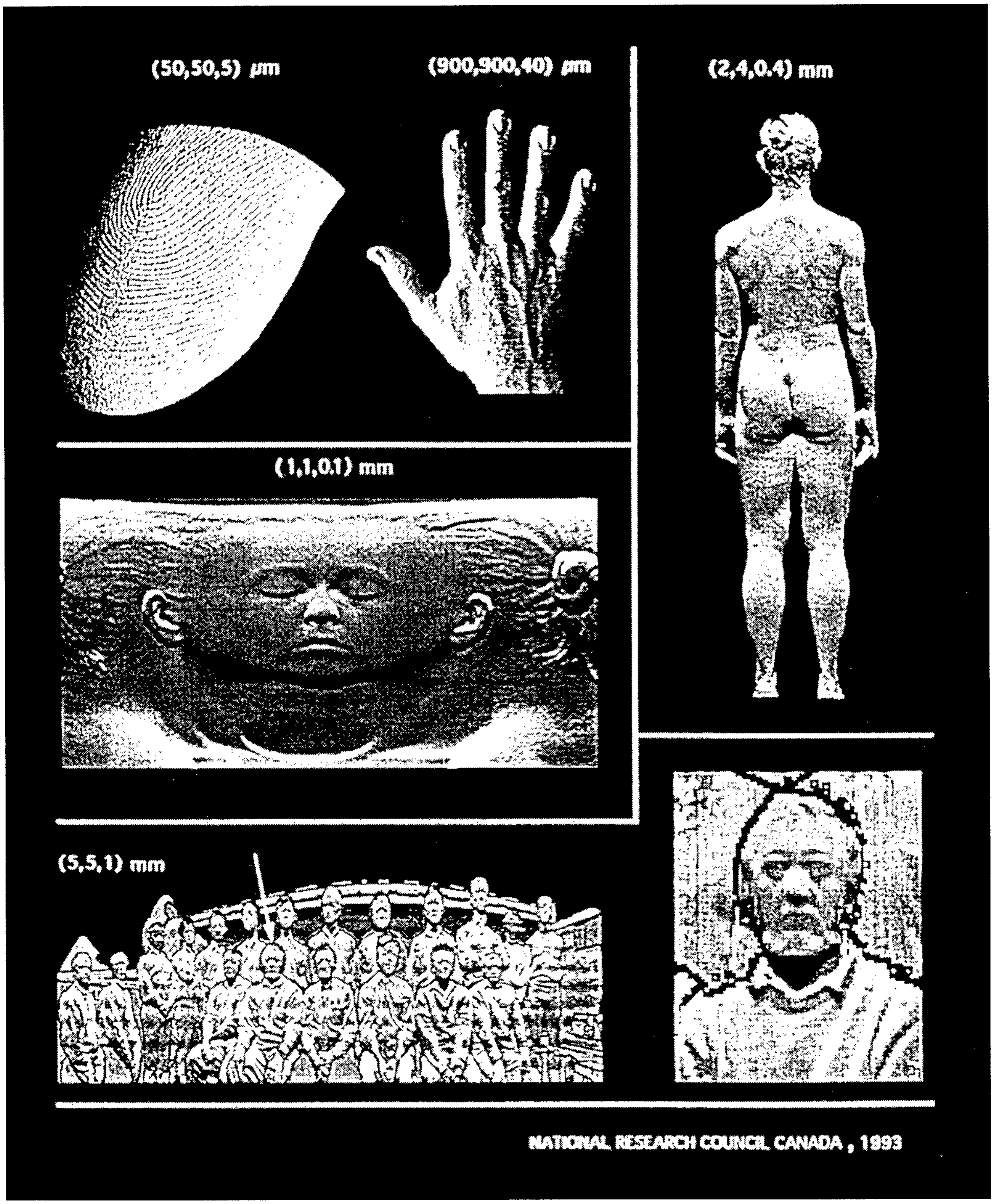


Figure 3-8. Illustrations of 3-D surface scan at various resolutions. The first number in brackets is the sampling interval along the X axis (horizontal direction), the second number is the sampling interval along the Y axis (vertical direction) and the third number is the resolution along the Z axis (perpendicular direction). All illustrations are showing the derivative of the 3-D data.

Scanner type	A	B	C
Resolution (μm) (X,Y,Z)	50,50,5	250,250,50	2000,2000,400
Numerical resolution (LSB, 2 bytes)	1	10	30
Volume of view (cm)	6.5	65	195
File size (MB) 1024x1024x2bytes	2	2	2

Table 3-1. An example showing parameter values for a fixed file format of 2 MB.

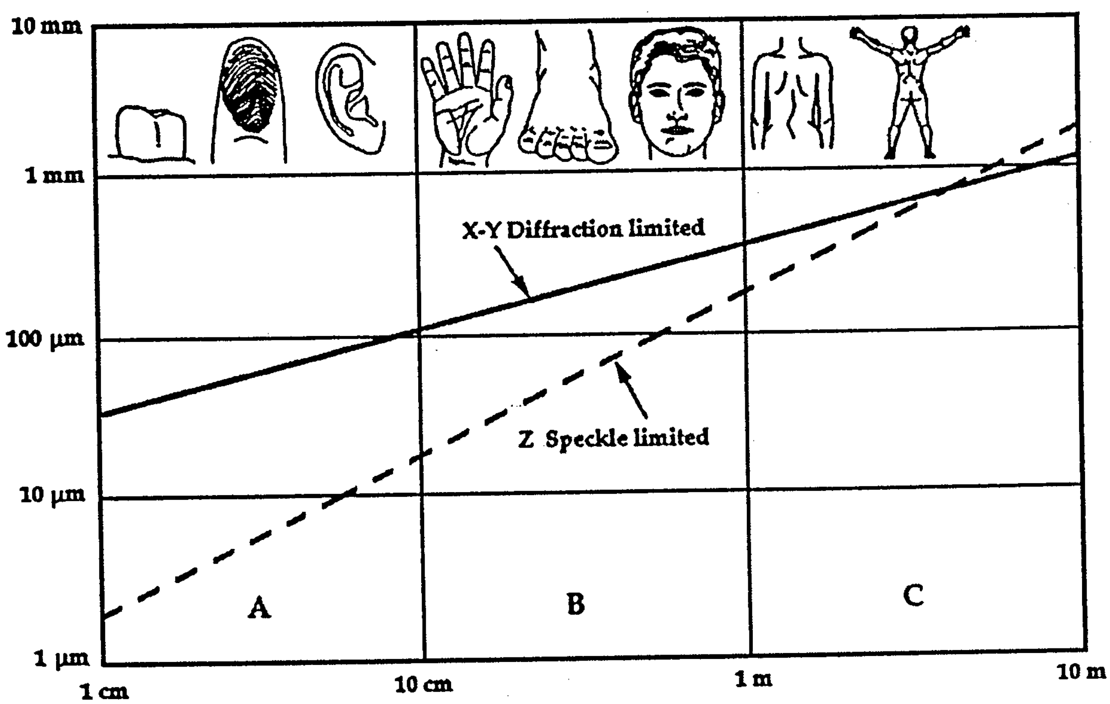


Figure 3-9. Resolution limits of 3-D optical measurements using laser light.

Spatial Definition

The above review of applications (Chapter II) of digital imaging of the human body shows clearly that spatial definition requirements are mainly related to the size of the body segments to be digitized. Scanning the shape of the cornea or the surface of a tooth necessitates sampling densities much higher than the surface of the trunk or of a leg.

Because most body segments are fairly smooth and regular in shape, it can be expected that changes in surface normals are the best way to specify spatial definitions. Essentially this means that each body segment (defined in its simplest form) needs approximately the same number of samples to define its shape. As an example, a finger segment would require for its definition about the same number of samples as a leg segment or an arm segment. On the other hand, one can expect to need a higher number of samples if the head is considered as a unique segment. This is due to the very different topology of the surface of the human face as compared to other body segments.

Limitations of Human Subjects

The human body is a living organism in constant motion. It is subjected to variations in shape from external (force of gravity) and internal factors. Shape variations of a subject are induced by changes in facial expression, sway, respiration, body fluid distribution, shifts in pose, pulsation of the blood and motor reflex correction for control of postural stability. Occlusion is another limitation imposed by the complexity of whole-body topology and the large number of degrees of freedom of its segments.

Skin pigmentation and scattering properties also limit the accuracy of measurement. Because the human skin is quite transparent (especially in the red portion of the visible spectrum), most optical sensing techniques will underestimate skin elevation. Studies of optical propagation in biological tissues can be found in Grossweiner et al. (1990), Arnfield et al. (1988), Yoon et al. (1987), and Bolin et al. (1987).

Last but not least, hair interference is likely to be the most difficult challenge in automating body surface anthropometric measurements. The distribution and density of hair is difficult to predict, dark pigmentation demands very high dynamic range optical sensing, and sampling density requirements for shape description are much too coarse to allow its resolution.

Camera Limitations

Speed is presently one of the most limiting factors for human body imaging. Few approaches are able to digitize the full body at a resolution appropriate for anthropometric studies. Typically, the acquisition time is more than 10 sec, which is long enough to be susceptible to most of the subject's shape variations mentioned above. Portable devices would be ideal, especially for large population database collection, but with the exception of the NKK mobile unit, there is no easy way to transport most of the full body 3-D imaging systems described in this review.

Laser-based systems have the advantage of depth of field, but they pose eye hazards, which necessitate either protection or proper camera design (see Henderson, 1984, for a brief review of laser radiation hazards). Eye-safety is achievable if the laser wavelength is selected in the 1.5 m range (Rioux et al., 1991), but the costs associated with the laser source and the optical sensing element are presently prohibitive. Generally speaking, the technology available to digitize the human body is difficult to operate, necessitates frequent calibration, and requires skilled operators to maintain performances.

Cost

Imaging laser radars are capable of accuracies from 50 to 5 m over depths of field 250 to 25,000 times larger. Usually they are expensive, with commercially available units starting at around $100,000. Triangulation sensors are capable of range accuracies over depths of field of 250 to 60,000 times larger than resolutions. Simple systems start at $1000 and range to several hundred thousand dollars. Moiré systems provide the same accuracy as triangulation sensors, but only if the surface constraints are met. Fast computer hardware needed for the computations will total more than $50,000 for a reasonably fast system. Holographic interferometer systems have the advantage of measuring with accuracies of less than 0.5 nm, but surface slope and smoothness constraints apply. Active focusing

systems hold promise as inexpensive range sensors, but high precision systems are not likely (Besl, 1988).

Conclusions

A number of methods are currently available to collect three-dimensional surface and subsurface detail on three-dimensional objects. Several techniques for surface imaging provide very accurate measurements of the human form. High-resolution computer tomographic images are already reconstructed to permit three-dimensional representation of internal structures. Other medical imaging methods of internal structures will allow similar capabilities.

Significant problems remain in producing a composite image with data collected from several sources. Standard body reference points and data formats are needed to allow direct comparison of these data. In addition, enhanced software tools and innovative displays will improve the usability of three-dimensional image data.

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CHAPTER IV: VISUALIZATION, MODELING AND ANALYSIS

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INTRODUCTION

Three dimensional anthropometry requires computer-based hardware and software tools for visualization, modeling and analysis. A networked computer graphics workstation with applications-oriented interactive image processing software is a practical means to satisfy these needs. 3-D anthropometry parallels other biomedical imaging disciplines, especially microscopy and diagnostic radiology, in its requirements for efficient and intuitive post-processing of large image or volume data sets. This chapter introduces current technology and methods for interactive biomedical digital image processing and analysis, emphasizing the computer-based tools applicable to 3-D anthropometry.

Interactive quantitative methods are required to extract and analyze multidimensional image data. Integrated interactive software is required for visualization and analysis of multimodality, multitemporal and multidimensional biomedical images. This software should be usable on any 2-D or 3-D imaging modality, and include interactive editing and quantitative mensuration tools. 3-D image segmentation, fusion, classification, and interactive volume rendering are often required. The software should be implemented entirely in a high-level language (C or C++) and operate on standard UNIX workstations.

The issue of rendering 3-D volumes has diverted interest from the importance of extracting objects from the 3-D volume. Once object definitions are available, object relationships can be defined. These are essential for the development of simulation, biomechanical and other studies. The accuracy of object surfaces as extracted needs to be known. This includes subpixel or fuzzy edge definition (an issue of precision) and the possibility that incorrect edges are being extracted (an issue of accuracy) (Falk et al., 1986). The complex form of the human body demands that the data from a scanning system possess a resolution proportional to surface curvature changes and an accuracy less than the desired resolution (Bajcsy, 1985).

This chapter summarizes recent developments in biomedical image processing and computer graphics, especially visualization, analysis, and modeling of surface and volumetric data sets. These elements are introduced in view of their contributions to satisfy the specific requirements of computer assisted 3-D anthropometry. Integrated software systems used for similar applications in science and engineering are identified. No single current software system satisfies all 3-D anthropometry requirements, and none is likely to do so in the near future. Interfacing and integrating existing software elements combined with an efficient and flexible means of developing new applications software is recommended as an effective approach to satisfy current and future requirements. Future trends are predicted, and a summary of the current state of the art is provided.

The next several years will see the maturing of a collection of technologies that will enable fully and transparently distributed computing environments. Networks will be used to configure independent computing, storage, and I/0 elements into "virtual systems" that are optimal for solving a particular problem. This environment will make the most powerful computing systems those that are logically assembled from network-based components and will also make those systems available to a widespread audience. Anticipating that the necessary technology and communications infrastructure will be available in the next 3 to 5 years, several research centers worldwide are developing and demonstrating prototype applications that test and exercise the currently available elements of this configurable environment. The Lawrence Berkeley Laboratory (LBL) Information and Computing Sciences and Research Medicine Divisions have

collaborated with the Pittsburgh Supercomputer Center to demonstrate one distributed application that illuminates the issues and potential of using networks to configure virtual systems (Johnston et al., 1992).

This application allows the interactive visualization of large three-dimensional (3-D) scalar fields (voxel data sets) by using a network-based configuration of heterogeneous supercomputers and workstations. The specific test case is visualization of 3-D magnetic resonance imaging (MRI) data. The virtual system architecture consists of a Connection Machine-2 (CM-2™) that performs surface reconstruction from the voxel data, a Cray Y-MP™ that renders the resulting geometric data into an image, and a workstation that provides the display of the image and the user interface for specifying the parameters for the geometry generation and 3-D viewing. These three elements are configured into a virtual system by using several different network technologies. The current status of the software, hardware, and communications technologies that are needed to enable this configurable environment have been identified. These interdependent technologies include: (1) user interface and application program construction methodologies, (2) the interprocess communication (IPC) mechanisms used to connect the software modules of the application, (3) the network protocols and interface hardware used by the IPC for communicating between modules running on separate and independent computing system elements, (4) the telecommunications infrastructure that provides the low-level data transfer functions for the networks that connect the geographically distributed elements used by the application, and (5) the nature of the functional elements that will be connected to form virtual systems.

Radiology is the principal domain for large-scale acquisition, processing and interpretation of medical images using digital technology. Computer applications in radiology are evolving rapidly, tied to incremental improvements in hardware, software, and methods. In computer hardware, the emergence of dramatically improved graphic and computational performance for engineering workstations enables their use for visualization. Major changes in networking, storage, and display technology play a major role in influencing applications. The use of three-dimensional digitizers to perform localization of real three-dimensional points in conjunction with images and the rendering of objects using rapid prototyping methods, such as stereolithography, were recently reported. Major software advances have taken place through the availability of applications packages that are operated with menu-driven or point-and-click user interfaces, data flow languages, or complete turnkey applications. Biomedical imaging methods for medical diagnosis now include CT, MR, US, PET, SPECT, digital radiography, biomagnetism, and optical range sensing. Each incorporate digital image acquisition and processing technology. Image processing for multimodality fusion or image registration, visualization, reconstruction, and quantification of images, have been reported. New computer methods to fabricate custom orthopedic implants, and to improve imaging technology assessment were recently introduced (Vannier et al., 1991). The acquisition of medical images and their display, manipulation, and applications have advanced rapidly throughout the 1980s and early 1990s. Magnetic Resonance (MR) imaging using ultra-fast echo planar and fast gradient-echo techniques have expanded application in cardiovascular studies, as well as in the brain and spinal cord. The recent emergence of spiral/helical CT has stimulated development of numerous new applications for x-ray transaxial computed tomography. The postprocessing of medical sectional images from MR imaging, CT, ultrasound, positron emission tomography, and single-photon emission CT have rapidly grown in importance. Other areas of growth include expanded applications of images in guidance of planning and performance of therapeutic procedures on patients through stereotactic techniques, intravascular ultrasound, robot surgery, and integrated displays. This more central role of three-dimensional imaging to medical care is new and will continue to grow. Research applications have recently appeared

in neuromorphometry, multimodality registration, functional neuroimaging, quantitative coronary angiography, and saturation MR techniques for myocardial tissue tagging (Vannier et al., 1992).

Image processing, visualization, and analysis software systems are available in many related fields of science and engineering: imaging satellites (Kruse et al., 1993), high performance computing and communications (Johnston et al., 1992), and especially diagnostic radiology (Vannier et al., 1991; Vannier et al., 1992).

Centers devoted to scientific visualization and analysis in multi-sensory systems that generate large volume datasets complement supercomputing facilities (Turcotte & Comes, 1993; Lang et al., 1993). The quest to deliver computers with teraflop computing power introduces several ancillary technical challenges. One of the most obvious challenges involves the capability to interpret the enormous quantity of data resulting from investigations using modern supercomputers. Data interpretation requires several techniques of scientific visualization to effectively support the analysis requirements of multi-sensory systems.

The need to more efficiently interpret large datasets led the U.S. Army Engineers Waterways Experiment Station to establish a scientific visualization center. This center, established in the fall of 1990, provides assistance with the adaptation and implementation of emerging data interpretation techniques to the 800+ researchers at the national laboratory. The collective experiences of the center with commercial visualization software, public domain software, internally developed software, visualization techniques, virtual reality systems, and hardware facilities was recently reported (Turcotte & Comes, 1993).

3-D anthropometry requires computer support, based upon digital imaging workstations analogous to those used in medicine. Computer applications in anthropometry are evolving rapidly, tied to incremental improvements in hardware, software, and methods. In computer hardware, the emergence of dramatically improved graphical and computational performance for engineering workstations enables their use for a variety of medical image visualization tasks, resulting in the emergence of versatile medical imaging workstations. Major changes in networking, storage, and display technology play a major role in influencing applications. The use of optical scanners to collect body surface 3-D points with sufficient density and resolution to enable generation of lifelike images, and rendering of derived objects using rapid prototyping methods such as stereolithography, is practical. Figure 4-1 shows the Cyberware WB4, a laser scanning system in use at government and military laboratories in the U.S.

Engineering Workstations

Engineering workstations became dramatically less expensive with much higher performance in 1993-1994. These workstations are self-contained units with color monitors and interactive UNIX-based software; for example, the Sun Microsystems, Inc. Sparcstation 10. Similar workstation systems are available from IBM, Digital Equipment Corp. (DEC), Silicon Graphics, Inc. (SGI), Hewlett-Packard (HP), and many others.

Networking in digital imaging applications is dominated by ethernet and the internet TCP/IP standards. ISDN or Integrated Systems Digital Networks operating at much higher speeds than the 10 MHz ethernet standard offer combined video, voice and digital communications. Among these the ATM or asynchronous transmission mode and FDDI Fiber Distributed Digital Interface standards have seen increasing utilization and acceptance, operating over fiber optic connections. The High Performance Computing and Communications (HPCC) initiative in the USA will yield an "electronic highway" in the next decade that builds upon the successful Internet computer network linking government, university and commercial organizations with high speed multimodal communications.

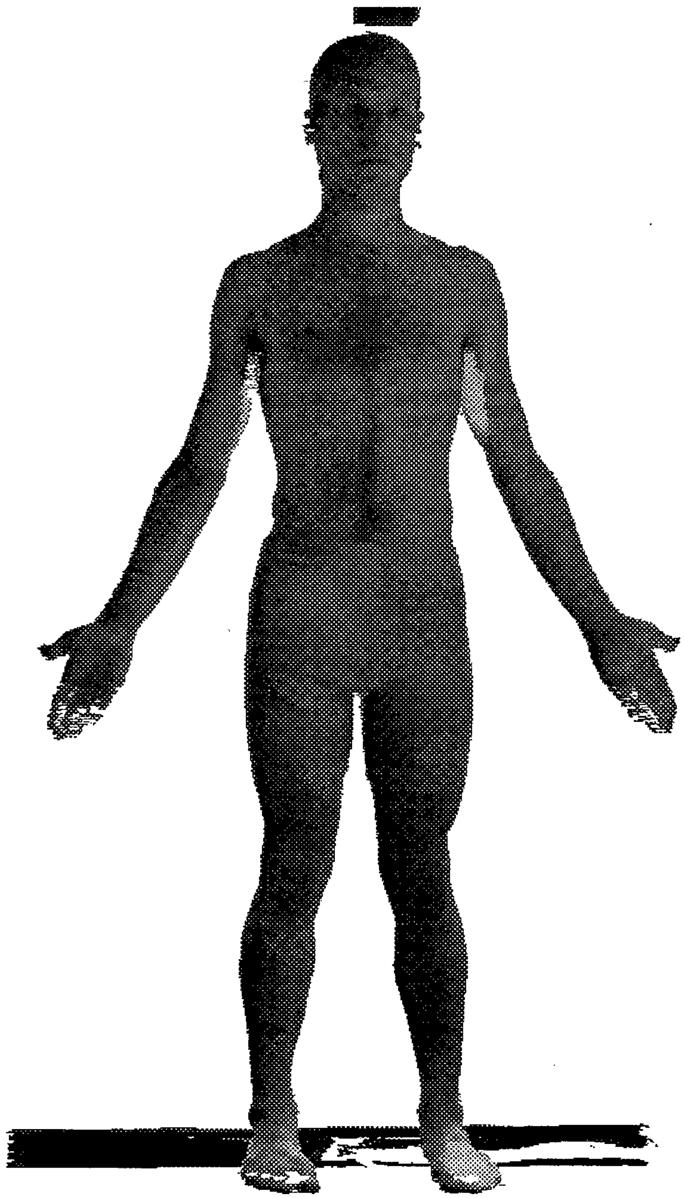

Figure 4-1. Scan taken by the Cyberware WB4 whole-body scanner.

3-D Anthropometry Workstation

Imaging workstations provide the means to view and manipulate pictures of body surfaces and internal structures. In medical imaging, interactive imaging workstations now frequently replace the familiar fluorescent viewbox used with film hardcopy images. Workstations provide electronic soft copy displays, facilitate image access, and enable useful interaction with the pictures under operator control. Figure 4-2 shows a digital image used in a study in which digitized images were measured to quantify wound healing (McQuiston, 1995).

Figure 4-2. Digitized image of a leg wound.

Medical imaging workstations are components of ultrasound, computed tomography, magnetic resonance imaging, and digital radiography systems found in medical radiology departments. They consist of a central processing unit or microprocessor, CRT display; local memory, network interface, and peripheral devices, especially disk drives (floppy, hard disk and optical drives). According to their intended use, these workstations are broadly classified as viewing, reporting or advanced display (and manipulation) systems.

In functionality, these workstations offer the same capabilities for image review and interaction as satellite display consoles (on CT and MR scanners), PACS display, 3-D imaging systems, and some networked personal computers. These functions include static and cine display, MR angiography (e.g., maximum intensity projection or MIP) display, multiplanar and 3-D reconstruction, multimodality image review, and image data base management.

User Requirements

The attributes of the image and non-image data determine the type of functions the 3-D Anthropometry workstation should support. Data qualities which should be considered for 3-D anthropometry imaging workstations include:

- Printing characteristics - for CRT displays, the character size and font for text and for images, the matrix size and bit depth.
- Timing - the rate and duration of data presentation. This is under almost absolute control of the users. In practical systems for data presented on CRTs, however, this may not be the case.
- Order - the position of data relative to other data.
- Grouping - the tendency of some data elements to have cohesion to other data elements, e.g. to satisfy anatomic or time relationships.
- Formatting - the physical arrangement of the data so as to impart meaning. Image "sorting" behavior is very likely to be involved in this aspect of data quality.
- Scaling - dimensioning the data to a particular standard. For imaging, this would refer to altering the physical size of some data displays to match others.
- Transiency - the transformation of data from one form into another during use or communication. Interpretation of images is one major example and forming images from parametric data is another.
- Quantity - the amount of data present. Users focus on a smaller group of images (if multiple), effectively limiting the data quantity.
- Complexity - the variety of functions implicit or explicit in the data. Biomedical image data tends to be very complex, especially if multidimensional.
- Relevancy - refers to how noisy the data is. For biomedical imaging, there is often a large component of structured noise present; whether data is noise or signal, is task dependent.

The information processing functions for medical image data are derived from techniques of subspecialty areas of computer science, such as computer vision, computer graphics, modeling and man-computer-interaction.

Personal Computer Platforms as Imaging Workstations

Personal computing environments such as the Macintosh II and IBM PC-compatible families

are suitable platforms for operating 3-D anthropometry imaging software systems. The Siemens LiteBox ™ is an example that is robust, and user-friendly. The SpyGlass products include Transform, Dicer and Format to perform visualization of multidimensional data sets represented in any of a large variety of formats. DipStation ™, Enhance, Adobe Photoshop, Image-Pro, and public domain programs (NIH/NIMH Image Software from Wayne Rasband) are principally two-dimensional image processing application systems for personal computers. Each of these has characteristic advantages that enable a user of an Apple Macintosh or IBM-PC-compatible with color display to perform image processing operations that in the past could only be done with more expensive high performance workstations. In the past, such image manipulations were available *only* with systems costing $25,000 and up. Today, they are feasible with $10,000 or less systems. This makes relatively high image processing functionality available at low cost on currently available hardware.

INTERACTIVE IMAGE PROCESSING SOFTWARE SYSTEMS

VI^{2}STA is a comprehensive menu-driven multiplatform digital image processing system from International Imaging Systems, primarily used in remote sensing and intelligence applications that operate on Sun and SGI workstations. AIPS , the Astronomical Image Processing System is used in optical and radioastronomy as a general purpose image processing software toolset. ELAS, the Earth Resources Laboratory Application System is used for the analysis of airborne and satellite multispectral and multitemporal datasets for remote sensing of environment.

Integrated image processing, visualization and analysis software packages have been developed for applications in science and engineering. Among these are ANALYZE, SIPS, RSYST, MEDIMAN, VIDA, INTEGRATE, and 3-D VIEWNIX.

Analyze: A software system for interactive and quantitative visualization of multidimensional biomedical images.

A comprehensive software system called ANALYZE has been developed which permits detailed investigation and evaluation of 3-D biomedical images. The software can be used with any 2-D or 3-D imaging modality, including x-ray computed tomography, radionuclide emission tomography, ultrasound tomography, magnetic resonance imaging and both light and electron microscopy. The package is unique in its synergistic integration of fully interactive modules for direct display, manipulation and measurement of multidimensional image data. Several original algorithms are included which improve image display efficiency and quality. One of the most versatile and powerful algorithms is interactive volume rendering, which is optimized to be fast without compromising image quality. An important advantage of this technique is to display 3-D images directly from the original data and to provide on-the-fly combinations of selected image transformations and/or volume set operations (union, intersection, difference, etc.). The inclusion of a variety of interactive editing and quantitative mensuration tools significantly extends the usefulness of the software. Any curvilinear path or region-of-interest can be manually specified and/or automatically segmented for numerical determination and statistical analyses of distances, areas, volumes, shapes, densities and textures. ANALYZE is written entirely in "C" and runs on several standard UNIX workstations. It is being used in a variety of applications by over 40 institutions around the world, and has been licensed by Mayo to several imaging companies. The software architecture permits systematic enhancements and upgrades which has fostered development of a readily expandable package. ANALYZE comprises a powerful "visualization workshop" for rapid prototyping of specific application packages, including applications to interactive surgery simulation and radiation treatment planning. ANALYZE offers the potential to accurately and reproducibly examine, from images, the structure and function of any cell, tissue, limb, organ or organ system of the body, much like a surgeon

or pathologist might do in practice, but entirely non-invasively, without pain or destruction of tissue (Robb & Barillot, 1988; Robb et al., 1989; Robb & Hanson, 1991).

Spectral Image-Processing System (SIPS): Interactive Visualization and Analysis of Imaging Spectrometer Data

The Center for the Study of Earth from Space (CSES) at the University of Colorado, Boulder, has developed a prototype interactive software system called the Spectral Image Processing System (SIPS) using IDL (the Interactive Data Language) on UNIX-based workstations. SIPS is designed to take advantage of the combination of high spectral resolution and spatial data presentation unique to imaging spectrometers. It streamlines analysis of these data by allowing scientists to rapidly interact with entire datasets. SIPS provides visualization tools for rapid exploratory analysis and numerical tools for quantitative modeling. The user interface is X-Windows-based, user friendly, and provides "point and click" operation. SIPS is being used for multidisciplinary research concentrating on use of physically based analysis methods to enhance scientific results from imaging spectrometer data. The objective of this continuing effort is to develop operational techniques for quantitative analysis of imaging spectrometer data and to make them available to the scientific community prior to the launch of imaging spectrometer satellite systems such as the Earth Observing System (EOS) High Resolution Imaging Spectrometer (HIRIS) (Kruse et al., 1993).

RSYST: A scientific software application environment (University of Stuttgart)

RSYST is a scientific software application environment at the University of Stuttgart. The architecture of the software system matches well with the hardware configuration of the University Computer Center, and the environment transparently integrates users, who are distributed throughout Germany, into a consistent software and hardware environment. The visualization concept at RUS and distributed visualization packages implemented at RUS was formulated to support diverse distributed research applications. A European sponsored project, PAGEIN, is consistent with these developments at RUS. The goal of this project is to experiment with future cooperative working modes of aerospace scientists in a high speed distributed supercomputing environment. Project results have been reported in the context of anticipated needs in scientific application environments (Lang, 1993).

MEDIMAN: an object-oriented programming approach for medical image analysis

Mediman is a new image analysis package which has been developed to analyze quantitatively Positron Emission Tomography (PET) data. It is object-oriented, written in C++ and its user interface is based on InterViews on top of which new classes have been added. Mediman accesses data using external data representation or import/export mechanism which avoids data duplication. Multimodality studies are organized in a simple database which includes images, headers, color tables, lists and objects of interest (OOI's) and history files. Stored color table parameters allow one to focus directly on the interesting portion of the dynamic range. Lists provide the capability to organize the study according to modality, acquisition protocol, time and spatial properties. OOI's (points, lines and regions) are stored in absolute 3-D coordinates allowing correlation with other co-registered imaging modalities such as MRI or SPECT. OOI's have visualization properties and are organized into groups. Quantitative ROI analysis of anatomic images consists of position, distance, volume calculation on selected OOI's. An image calculator is connected to Mediman. Quantitation of metabolic images is performed via profiles, sectorization, time activity curves and kinetic modeling. Mediman is menu and mouse driven, macro-commands can be registered and replayed. Its interface is customizable through a configuration file (Coppens et al., 1993).

VIDA: An Environment for Multidimensional Image Display and Analysis

VIDA is a new image display andquantitation package written in C under the UNIX operating system that uses the Xview toolkit to conform to the Open Look graphical user interface specification. A shared memory structure has been designed which allows for the manipulation of multiple volumes simultaneously. VIDA utilizes a windowing environment and allows execution of multiple processes simultaneously. Available programs include: oblique sectioning, volume rendering, region of interest analysis, interactive image segmentation/editing, algebraic image manipulation, conventional cardiac mechanics analysis, homogeneous strain analysis, tissue blood flow evaluation and others. VIDA is built modularly, allowing new programs to be developed and integrated easily. Emphasis has been placed upon image quantitation for physiological evaluation studies (Hoffman et al., 1992; Sundarmoorthy et al., 1992).

INTEGRATE: 3-D Image visualization, manipulation, and analysis software for UNIX-based workstations.

INTEGRATE was developed at the CARD Laboratory, one of the Armstrong Laboratories at Wright-Patterson Air Force Base in Dayton, Ohio, in 1994. Air Force researchers have used INTEGRATE to test and evaluate new helmet systems, develop augmentive files for surface scan databases, record human-equipment interface geometries, and prepare surface data for rapid prototyping systems. INTEGRATE was developed as a prototype, which explains its fairly basic user interface, but it provides many unique functions for working with surface data, and CARD engineers plan to add more features in future versions (Burnsides, Files, & Whitestone, 1996).

3-D VIEWNIX: A medical image processing software system for UNIX-based workstations of the University of Pennsylvania by J.K. Udupa and associates.

3-D VIEWNIX is a data-, machine-, and application-independent software system, developed and maintained on an ongoing basis by the Medical Image Processing Group. It is aimed at serving the needs of biomedical visualization researchers as well as end users. Unlike existing visualization packages, 3-D VIEWNIX is not designed around a fixed methodology or set of methods providing a fixed set of tools. It incorporates the basic imaging transforms common to most visualization and analysis methods and provides a facility to combine them in meaningful ways. The result is a powerful exploratory environment that not only provides the commonly used standard tools but also an immense variety of others. In addition to visualization, it incorporates a variety of unique tools for multidimensional image analysis. Its design is mostly image data dimensionality independent to make it just as convenient to analyze 2-D and 3-D data as it is to analyze 4-D and higher-dimensional data. It is based on UNIX, C, X Window and our own multidimensional generalization of the 2-D ACR-NEMA standards for image data representation (Udupa et al., 1993).

BIOMEDICAL VISUALIZATION

This section addresses the practical issues encountered in applying advanced biomedical visualization methods to surface and volume data sets. User interface, technique comparison, analogy with cartographic methods applied in a geographic information system (GIS), volume visualization methods, portable and low cost implementations are considered.

Biomedical investigators are currently able to acquire and analyze physiological and anatomical data from three-dimensional structures in the body. Often, multiple kinds of data can be recorded simultaneously. The usefulness of this information, either for exploratory viewing or for presentation to others, is limited by the lack of techniques to display it in intuitive, accessible formats. Unfortunately, the complexity of scientific visualization techniques and the inflexibility of commercial packages deter investigators from using sophisticated visualization methods that could provide added insight into

the mechanisms of the phenomena under study. The sheer volume of such data is a problem. High-performance computing resources are often required for storage and processing, in addition to visualization.

A language-based interface that allows scientists with basic programming skills to classify and render multivariate volumetric data with a modest investment in software training has been developed. The interface facilitates data exploration by enabling experimentation with various algorithms to compute opacity and color from volumetric data. The value of the system is demonstrated using data from cardiac mapping studies, in which multiple electrodes are placed in and on the heart to measure the cardiac electrical activity intrinsic to the heart and its response to external stimulation (Palmer et al., 1992).

Surface and Volume Visualization

Many surface rendering techniques are currently available for the three-dimensional display of structure data captured by imaging devices. Comparatively fewer volume rendering techniques are also available for the same purpose. The relative performance of these two methodologies in visualization tasks has been the topic of much recent discussion. Although it is very desirable to establish, based on observer studies, objective guidelines stating the relative merits of the two methodologies, it is impossible to conduct meaningful observer studies that take into account all of the large number of rendering techniques and their numerous controlling parameters. Therefore, comparison of the two methodologies has been made on a technical basis to understand strengths and weaknesses (Udupa et al., 1991).

The comparison of surface and volume rendering methods for discrete uniformly sampled image data sets encountered in medical x-ray computed tomography and magnetic resonance imaging has been performed. The bases of comparison are: ability to portray thin bones; clarity of portrayal of sutures, fractures, fine textures, and gyrations; smoothness of natural ridges and silhouettes; and computational time and storage requirements. The underlying algorithms have been evaluated to determine how they behave under each of these comparative criteria. At the current state of development, the surface method has a slight edge over the volume methods for portrayal of information of the type described above and a significant advantage considering time and storage requirements, for comparable implementations (Udupa et al., 1991).

Cartographic Visualization

Geographic Information Systems (GISs) are widely used tools for the collection, management, and display-or visualization-of many types of data that describe space. Visualization of spatial data has been the domain of expertise of cartographers and elaborate recommendations for best rendering of spatial data exist. Unfortunately, this body of knowledge is not cast yet into a formalization and thus is not accessible immediately for programming GIS software. A particular problem is the description of the rendering parameters for complex spatial objects.

A method for describing the set of individual geometric objects parts to which different rendering parameters can be assigned was developed. The geometric data model uses the concepts of boundary and interior, and their specializations for returning objects of particular dimensions. It is applicable equally to both raster and vector data, and, therefore, a contribution to the integration of vector and raster GIS. The rendering parameters are based upon Bertin's "visual variables." Abbreviated class definitions in C++ are included as a method to describe formally the concepts treated (Frank & Egenhofer, 1992).

Volume Visualization

Conventional computed tomographic display formats are not optimal for demonstrating three-dimensional anatomic relationships. In otolaryngology--head and neck surgery these critical relationships are often highly complex, and their complete understanding is essential to a successful surgical outcome. Computer-generated image display format via volume rendering facilitates the understanding of these critical anatomic

relationships by transforming conventional imaging data into clinically relevant 3-D images. Unlike 3-D surface reconstruction algorithms, volume rendering suffers minimal data loss in the conversion process, which in turn provides for superior image resolution. This better allows the application of 3-D technology to small or complicated anatomic structures such as those frequently encountered in otolaryngology--head and neck surgery (Davis et al., 1991).

Ray-tracing methods are frequently used for visualizing volumetric data. To evaluate the performance of specific implementations, two classes of volumetric data are employed. The first consists of the probability density functions of a physical variable, such as the states of an electron in hydrogen atom and represents the case of visualizing data derived from analytical expressions. The second class of volumetric data is a set of three-dimensional fractals which are generated over regular three-dimensional Cartesian grids of various sizes. The motivation for generating and visualizing the fractal data sets is two-fold. Firstly, a fractal data set allows verification of the correctness of the implementation. Secondly, modeling with fractals is practical for an important class of biomedical problems, and visualization of these models is useful in their interpretation. Ray-tracing is computationally expensive and CPU timings are a typical performance metric for a representative set of images (Ramesh & Athithan, 1993).

Portable Image-Manipulation Software

The visualization and manipulation of images provided by different imaging modalities constitutes one of the most challenging component of a digital biomedical imaging system environment. It is often necessary to provide this visualization software on a different workstation type because of the varying requirements imposed by the range of applications. The user interface must be the same, independent of the underlying workstation. In addition to a standard set of image-manipulation and processing tools, there is a need for more specific clinical tools that can be easily adapted to specific medical requirements.

To achieve this goal (initially at UCLA and now Geneva), it was elected to develop a modular and portable software called OSIRIS. This software is available on two different operating systems (the UNIX standard X-11/OSF-Motif based workstations and the Macintosh family) and can be easily ported to other systems. The extra effort required to design such software in a modular and portable way was worthwhile because it resulted in a platform that can be easily expanded and adapted to a variety of specific clinical applications. Its portability allows users to benefit from the rapidly evolving workstation technology and to adapt the performance to suit their needs (Ligier et al., 1992).

PC-based 3-D Visualization System for CT/MR Data Volumes

Three-Dimensional (3-D) CT and MR image post-processing has been developed on low-cost 3-D imaging system that can provide a level of performance sufficient to meet typical needs. Hardware considerations of a generic system include display characteristics, processor performance and storage capacity that are typical of commonly available personal computers (PCs). Given a 3-D image as a stack of slices, a packed binary cubic voxel array is interpolated from the original scan data set, by efficiently combining segmentation (density thresholding), interpolation, and packing. Since threshold-based segmentation is very often not perfect, object-like structures and noise clutter the binary scene. An effective mechanism to isolate the object from this clutter is by tracking a specified, connected surface of the object. The surface description thus obtained is rendered to create a depiction of the surface on a 2-D display screen. Efficient implementation of hidden-part removal and image-space shading and a simple and fast antialiasing technique provide a level of performance which otherwise would not have been possible in a PC environment (Raya et al., 1990).

Computer-Based Morphometry

Anthropometry implies morphometry at the gross anatomic level. However, the computer-

based methods developed for microscopy and stereology extrapolate directly. In order to use these methods, it is often necessary to correct the data sets for the presence of radiometric and geometric distortions. This has recently been reported in MRI post-processing.

Stereology, or the derivation of quantitative, three-dimensional (3-D) data about cells by statistical analysis of the structures of random sections, is widely used in cytology and pathology. However, there are situations where this approach is inadequate, and only an analysis of a homogeneous population of whole cells will give the required results. This involved 3-D reconstruction from physical or optical sections, or tomography or photogrammetry of whole-cell mounts. Stereo viewing individual sections or projections adds considerably to the information available for both contouring and reconstruction. Recent image-processing advances in clinical radiography have shown, for the first time, that rapid, high-resolution digitization and contrast enhancement enable nearly all structural details to be routinely extracted from the micrographs and adequately portrayed. 3-D whole-cell reconstructions provide the digital data for many kinds of morphometric measurements on both whole cells and their individual organelles and membranes (Parsons et al., 1990).

The use of computers in morphometry can involve 1) automated image analysis, semiautomated image analysis and point, intersection, intercept and profile counts of two-dimensional images on tissue sections with mathematical extrapolation to the third dimension, 2) direct measurement of volumes, surfaces, lengths, and curvature using x,y,z coordinates of serial sectioned images; or 3) stereologic techniques and serial sections which is a combination of 1 and 2 above. Automated and semiautomated image analyses are generally restricted to specimens that are characterized by differential contrast. Point, intersection, and profile counts using hand-held, notebook PCs, portable PCs, or standard PCs and MS-DOS-based application programs are extremely efficient, precise, affordable, and convenient methods of quantitating average values of a population. When morphometric measurements of individual structures are required, computer-assisted three-dimensional reconstruction using x,y,z coordinates of the surface outline from serial sections is a tedious yet precise method.

A computer program that efficiently estimates mean caliper diameter, volume, and surface area with less than five percent error with five sections per structure was developed. Another program that does digital image subtraction on serial sections, superimposes digitally generated test systems on biological images, and accumulates point, intersection, and profile counts was developed using a Macintosh II series computer (Hyde et al., 1992).

MR Image Correction Procedures - Modality-Specific Pre-Processing

Segmentation of a feature of interest while correcting for partial volume averaging effects is a major tool for identification of hidden abnormalities, fast and accurate volume calculation, and three-dimensional visualization in the field of magnetic resonance imaging (MRI). The optimal transformation for simultaneous segmentation of a desired feature and correction of partial volume averaging effects, while maximizing the signal-to-noise ratio (SNR) of the desired feature has been defined. It was proved that correction of partial volume averaging effects requires the removal of the interfering features from the scene. It is also proved that correction of partial volume averaging effects can be achieved merely by a linear transformation. It is finally shown that the optimal transformation matrix is easily obtained using the Gram-Schmidt orthogonalization procedure, which is numerically stable. Applications of the technique to MRI simulation, phantom, and brain images are shown. In all cases the desired feature is segmented from the interfering features and partial volume information is visualized in the resulting transformed images (Soltanianzadeh et al., 1993).

Stereotactic Image Localization

The precise and accurate location of internal body structures must be known to plan and affect treatment. In much the same way that body surface landmarks are used to characterize the geometry of human form, stereotactic principles - adapted from close range photogrammetry - directly apply to body surface anthropometry. The principal tools include image registration and multimodality software. The development of frame-based and frameless stereotactic imaging systems is reviewed. A natural extension to the multimodality systems is a multitemporal image processing and registration system.

The planning and administration of three dimensional radiosurgery requires accurate stereotactic localization of small lesions through imaging. Usually this is accomplished by attaching a rigid frame to the patient's skull and collecting images that can be localized by referencing the coordinate system of the frame itself. Alternatively, frameless stereotaxy implies that the intrinsic coordinate system of the body part (typically the head) can be used to co-localize sites of interest based upon the images themselves, obviating the necessity for the attached rigid reference frame. Frameless stereotactic localization is a relatively recent development, and is now used in some applications, especially multimodality imaging.

A comprehensive software package has been developed for visualization and analysis of 3-dimensional data sets. The system offers a variety of 2- and 3-dimensional display facilities including highly realistic volume rendered images generated directly from the data set. The package has been specifically modified and successfully used for stereotactic radiosurgery treatment planning. The stereotactic coordinate transformation is determined by finding the localization frame automatically in the CT volume. Treatment arcs are specified interactively and displayed as paths on 3-dimensional anatomical surfaces. The resulting dose distribution is displayed using traditional 2-dimensional displays or as an isodose surface composited with underlying anatomy and the target volume. Dose volume histogram analysis is an integral part of the system. An overview of volume rendering methods and the application of these tools to stereotactic radiosurgery treatment planning has been reported (Gehring et al., 1991).

Frame-based stereotactic systems provide valuable localization information for the performance of neurosurgical procedures. State-of-the-art systems provide for sophisticated preoperative planning and intraoperative interactive help with resection of predefined tissue volumes, providing assistance with resection of intrinsic brain tumors whose margins may not be readily visible at the time of surgery. There remain, however, a majority of neurosurgical procedures that would benefit from some form of localization but for which the application of a cumbersome frame and arc system is inconvenient. Frameless stereotactic localization or "cranial-based" localization provides a rapid and convenient means for computer-interactive localization and surgery for many of these cases. The stereotactic operating arm system is designed to complement frame- based stereotactic surgery, bringing standard neurosurgical procedures into the realm of computer-assisted interactive localization. The pace of progress is such that eventually, some form of computer interactive cranial localization will become a common neurosurgical tool. The concept of frameless localization is taken a step further in the frameless radiosurgical system described above. It is reasonable to think that this concept of "automated feature recognition," whether for recognizing scalp or bone contours, will ultimately become the foundation of procedures requiring cranial localization with reference to previously obtained digital images (Guthrie & Adler, 1992).

MULTIMODALITY IMAGE PROCESSING: IMAGE REGISTRATION AND CORRELATION

Image correlation techniques can provide objective spatial registration between multimodality data sets acquired during the planning and follow-up phases of radiation

therapy. Correlation of pre-CT/MRI with follow-up CT/MRI and 3-D dose matrices may provide insights into normal tissue tolerance. Correlation of SPECT and planar scintigraphs with anatomical maps derived from CT/MRI may be useful in the precise localization of disease and in the evaluation of new modalities, such as radiolabeled monoclonal antibodies, in the diagnosis and treatment of cancer. Correlation of PET and MRI may lead to a more precise understanding of structure-function relationships of the brain. The development and refinement of multimodality image-correlation techniques is a logical step in the evolving role of imaging in radiation therapy (Chen et al., 1990).

A surface matching technique has been developed to register multiple imaging scans of the brain in three dimensions, with accuracy on the order of the image pixel sizes. Anatomic information visualized in X-ray CT and magnetic resonance images may be integrated with each other and with functional information from positron emission tomography. Anatomical structures and other volumes of interest may be mapped from one scan to another, and corresponding sections through multiple scans may be directly compared. This capability provides a novel quantitative method to address the fundamental problem of relating structure to function in the brain. Applications include basic and clinical problems in the neurosciences and delivery and assessment of brain tumor therapy (Pelizzari et al., 1989).

Magnetic resonance imaging, computed tomographic, and positron emission tomographic studies of the brain provide complementary information, and many patients undergo more than one of these studies during the course of their diagnostic workup and treatment. Techniques for quantitative geometric correlation of such studies make it possible to create integrated multimodality images by mapping features from one image onto an image obtained with another modality. In the Pelizzari and Chen method (Pelizzari et al., 1989) the coordinate transformation between any pair of images is found by a semiautomatic algorithm for matching models of the patient's external surface as depicted in the two data sets. The resultant hybrid images, which combine complementary features of different studies, are often more useful for diagnosis and treatment planning than are the original single- modality images. The algorithm can also be used for spatial registration of baseline studies with follow- up images created with the same modality, which allows tracking of a lesion to detect subtle interval changes in size and shape. This technique can be applied to images acquired in routine clinical practice, since it is completely retrospective and does not necessitate special positioning or landmarking of the patient (Levin et al., 1988).

For the normal physiological responses of the brain or the pathophysiological changes that accompany disease states to be evaluated, it is necessary to compare data sets between different imaging modalities for individual subjects. Similarly, it is important to compare data between individuals both within and across imaging modalities for individual subjects. In a collaborative project with a number of university groups a system that allows for the within-subject alignment and registration of three-dimensional data sets obtained from different modalities for the same individual was developed. This analysis takes into account the error induced by image acquisition, registration and alignment with regard to scaling, translation and rotation. A more difficult problem is the between-subject warping of individual brain anatomy to match that of another individual or of an idealized model. If the principles of morphometrics and homologous landmarks are applied, three-dimensional brain warping can provide this type of between-subject comparison. The results of accomplishing these two tasks is a system that allows data obtained in a given individual to be compared across structure and function, as obtained from magnetic resonance imaging (MRI) and from positron emission tomography (PET), respectively. It also allows comparison of the resultant information with averaged between-subject data from populations of normal individuals or patients with specific neurological disorders. This system provides the means by which to compare quantitative data between

individuals in an objective and automated fashion (Mazziotta et al., 1991).

Image registration is important for numerous imaging applications such as three-dimensional reconstruction, multimodality correlations, image averaging and subtraction. Methods used for image registration are based upon either the shape and form of the image pairs or their densitometric relationships. There are five different registration methods: frequency domain cross-correlation, spatial domain cross-correlation, principal axes/center of mass, fiducials and manual. These methods were compared in terms of their accuracy, efficiency and application with several different data types including different species and modalities. The underlying mathematical bases were compared. The results of the comparisons showed that image quality influenced the behavior of all methods. Images of the blockface provide an excellent reference for subsequent registration. These results also suggest that the statistical performance of various methods is not a reliable metric when distant and different images are registered. Visual comparisons by image overlap and pixel differencing illustrated that some methods are more prone to rotational error than others, especially when repeated pairwise registrations were computed along the rostral/caudal axis (Toga & Banerjee, 1993). Figure 4-3 provides an example of a fiducial registration method used to visualize helmet fit (Whitestone & Robinette, 1996).

Multitemporal Image Registration

Image registration is a very important operation in multichannel image applications to correct for the frame-to-frame displacement that occurs during the image acquisition process. In order to register a pair of images, an image registration algorithm often employs some similarity criterion between the image functions, testing different displacement vectors to find an extremum of this similarity measure. A good similarity criterion should be robust with respect to the diverse noise environments encountered in multichannel image applications. Misregistration often leads to invalid results in later image processing stages. A new similarity measure based on the number of coincident bits in multichannel images is presented. The similarity criterion incorporated in the image registration algorithm uses a coincident bit counting (CBC) method to obtain the number of matching bits between the frames of interest. The CBC method not only performs favorably compared with traditional techniques, but also renders simpler implementation in conventional computing machines. An image registration algorithm which incorporates the CBC criterion is proposed to determine the translational motion among sequences of images. The analysis of the errors caused by noise, misregistration, and a combination of these two is also included. Some experimental studies using low-contrast coronary images from a digital angiographic sequence have been performed. The results compare favorably with those obtained by using other nonparametric methods. Applications for this algorithm include digital angiography and mammography (Chiang & Sullivan, 1993).

Electronic Anatomic Atlases

The development of electronic anatomic atlases of the body is an active area of research and development. The simplest of these uses an analog videodisk to store pre-computed image sequences. Much more general and complex digital 3-D systems have been constructed. We anticipate that these will evolve to become central to the user interface for future 3-D anthropometry systems. The matching of atlas datasets with individual scan volumes has recently been reported.

Analog Videodisk Atlas of the Head

The interactive visualization of animated images through a computerized three dimensional (3-D) full color model of an unstained cadaveric human head is presented. Serial full color images were taken of the blockface of a cryomicrotomed frozen human head every 200 microns. From this series of images a three dimensional digital model with a resultant pixel resolution of 200 $micron^3$ was created on a UNIX work-station.

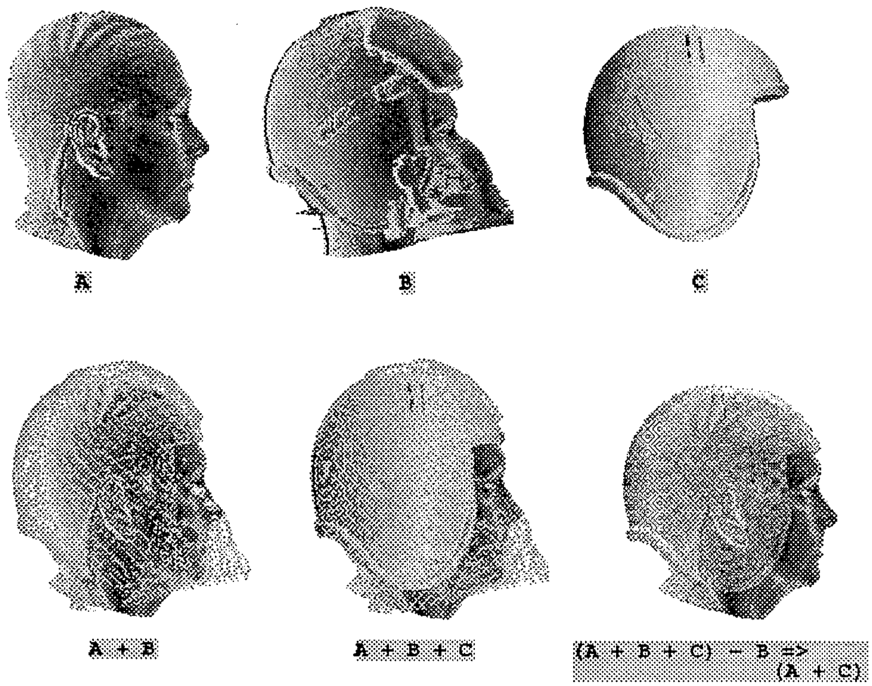

Figure 4-3. Example of a fiducial registration method.

Using this database, resampled images were computed along orthogonal axes and written sequentially to a write-once-read-many times (WORM) videodisc unit. Playback of this customized videodisc dataset provides animations of the digitally reconstructed slices and 3-D reconstructed surface models. An interactive interface to the animated sequences is provided through a PC based tutorial package. This tutorial program is able to access videodisc frames to display animations and labeled still images in a software window to illustrate various neuroanatomic topics. The technique of animation as applied to this high resolution 3-D model provides insight into complex spatial relationships and has great potential in research and as a teaching tool (Narayan et al., 1993).

Computerized three-dimensional atlas of the human skull and brain.

An electronic interactive anatomic atlas of the human head based on a volume model derived from MR and CT was developed. Every voxel of this model was labeled by a neuroanatomist concerning its membership to a structural and/or functional region. A computer program (Voxel-Man) was written that, instead of displaying precomputed images, allows the user to choose and compose arbitrary views. This system allows the user to subtract parts and ask for annotations using a mouse. Conversely, one can compose images by choosing objects from the list of anatomical constituents which is displayed on the screen. A set of dissection tools allows a "look and feel" that comes near to a true dissection. Operations that are not possible in a real dissection, such as reassembly or filling cavities, can be performed. This computerized model can be used for anatomy teaching and as a reference for radiologists or surgeons. To replace classical atlases, the spatial resolution must be improved and speed must approach real time. Functional imaging data (position emission tomography and single photon emission CT) can be added to the system. The system is mobile and can be situated in classrooms, operating rooms, reading rooms, and libraries (Tiede et al., 1993).

Electronic Atlas for Image Volume Co-Registration

Data fusion in medical imaging implies merging multimodal and multipatient images, identification of structures and 3-D display. Data fusion in medical imaging can be seen into two ways (i) multisensors fusion of anatomical and functional information and (ii) interpatient data fusion by means of warping models. These two aspects set the methodological framework necessary to perform anatomical modeling especially when concerning the modeling of brain structures. The major relevance of this work concerns the interpretation of multimodal 3-D neuro-anatomical data bases.

Three types of data fusion problems are considered in the medical literature. The first one concerns the problem of data combination which includes multimodal registration (multisensor fusion applied to CT, MRI, DSA, PET, SPECT, or MEG). In particular, the problem of warping patient data to an anatomical atlas has been solved with deformable templates using high order transformations. The second problem of data fusion addressed is the identification of anatomical structures by image analysis methods. Two techniques were developed: analysis of image geometrical features for determination of a fuzzy mask to label the structure of interest, and labeling major cerebral structures by statistical image features associated with relaxation techniques. Finally, the volume rendering and 3-D display of combined data adds additional complexity to the visualization tasks (Barillot et al., 1993).

The computerized brain atlas program (CBA) provides a powerful tool for the anatomical analysis of functional images obtained with positron emission tomography (PET). With a repertoire of simple transformations, the data base of the CBA is first adapted to the anatomy of the subject's brain represented as a set of magnetic resonance (MR) or computed tomography (CT) images. After this, it is possible to spatially standardize (reformat) any set of tomographic images related to the subject, PET images, as well as CT and MR images, by applying the inverse atlas transformations. From these reformatted

images, statistical images, such as average images and associated error images corresponding to different groups of subjects, may be produced. In all these images, anatomical structures can be localized using the atlas data base and the functional values can be evaluated quantitatively.
The purpose of this study was to determine the spatial and quantitative accuracy and precision of the calculated regional mean values. First, the spatial accuracy and precision of the reformation process were determined by measuring the spread of defined anatomical structures in the reformatted MR images of the subjects. Second, the mean global CBF and the mean rCBF in the average PET images were compared with the global CBF and rCBF in the original PET images. The results demonstrate that the reformation process accurately transformed the individual brains of the subjects into the standard brain anatomy of the CBA. The precision of the reformation process had an SD of approximately 1 mm for the lateral dislocation of midline structures and approximately 2-3 mm for the dislocation of the inner and outer brain surfaces. The quantitative rCBF values of the original PET images were accurately represented in the reformatted PET images (Seitz et al., 1990).

Computer-aided interpretation of SPECT (single photon emission computed tomography) images of the brain has been performed using an MRI-derived 3-D neuro-anatomical atlas. Nuclear medicine images have comparatively poor spatial resolution, making it difficult to relate the functional information which they contain to precise anatomical structures. A 3-D neuro-anatomical atlas has been generated from the MRI data set of a normal, healthy volunteer to assist in the interpretation of nuclear medicine scans of the brain. Region growing and edge-detection techniques were used to semi-automatically segment the data set into the major tissue types within the brain. The atlas was then labeled interactively by marking points on each 2-D slice. Anatomical structures useful in the interpretation of SPECT images were labeled. Additional, more detailed information corresponding to these structures is provided via an interactive index which allows access to images, diagrams and explanations. Registration of patient SPECT studies with the atlas is accomplished by using the position of the skull vertex and four external fiducial markers attached to the skin surface. The 3-D coordinates determined from these points are used to calculate the transformation required to rotate, scale and translate the SPECT data, in 3-D, to match the atlas. Corresponding 2-D slices from the two 3-D data sets are then displayed side-by-side on a computer screen. A cursor linking the two images allows the delineation of regions of interest (ROIs) in the SPECT scan based on anatomical structures identified from the atlas. Conversely regions of abnormal isotope distribution in the SPECT image can be localized by reference to corresponding structures in the atlas (Lehmann et al., 1991).

A system for elastically deforming a three-dimensional atlas to match anatomical brain images has been developed. This system was tested by generation of six deformed versions of an atlas. The deformed atlases were created by elastically mapping an anatomical brain atlas onto different MR brain image volumes. The mapping matches the edges of the ventricles and the surface of the brain; the resultant deformations are propagated through the atlas volume, deforming the remainder of the structures in the process. The atlas was then elastically matched to its deformed versions. The accuracy of the resultant matches was evaluated by determining the correspondence of 32 cortical and subcortical structures. The system on average matched the centroid of a structure to within 1 mm of its true position and fitted a structure to within 11% of its true volume. The overlap between the matched and true structures, defined by the ratio between the volume of their intersection and the volume of their union, averaged 66%. When the gray-white interface was included for matching, the mean overlap improved to 78%; each structure was matched to within 0.6 mm of its true position and fit to within 6% of its true volume. Preliminary studies were also made to determine the effect of the compliance of the atlas on the resultant match (Gee et al., 1993).

Biological Shape Variation

Biological shape variation characterization has had little practical importance since methods for rigorous analysis have significantly lagged development of techniques for surface and volumetric data acquisition and manipulation in the last decade. It has not been possible to efficiently and reliably deal with biological shape variations in clinical medicine. Grenander and Miller (1991) have given us a new set of tools to understand biomedical silhouettes, projection radiographs, serial slices, and volumetric image data sets. Extension to three and four dimensions where shape varies with time, is anticipated.

Application to populations allows separation of individual differences from normal variation. Grenander and Miller's work (1992) will revolutionize allometry applied to study of normal and abnormal human growth and development, interspecies variation, and sexual dimorphism. Their method provides a mathematically tenable means to isolate markers for testing heritability of traits through quantitative genetic analysis.

Magnetic resonance imaging (MRI) has emerged recently as a major research and clinical modality to study the brain, heart, musculoskeletal system, and other organs and body regions. Despite great flexibility in conducting imaging experiments that yield high contrast among body tissues, the specificity for MRI is low. For example, reliable separation of normal brain tissue components such as gray matter, white matter, cerebrospinal fluid, and others, is very difficult.

Statistical pattern recognition has been applied with modest success based on feature extraction from observed measurements categorized according to a rule set into one of several tissue classes. Supervised methods are often required due to presence of instrument signature and measurement variations so fully automatic segmentation of MR data sets has not been practical. Superior results were demonstrated by Grenander and Miller with an important generalization of statistical pattern recognition to achieve what no other method has been able to do- increase the specificity of MRI.

Neuromorphometric studies of the brain in subpopulations afflicted with neuropsychiatric disorders is performed in vivo using magnetic resonance imaging, based upon the premise that symptomatic individuals share regional shape and volume differences which correspond to focal abnormalities. Identification of these sites requires high precision image analysis that cannot be achieved by manually, not to mention the tedium of processing large numbers of images. Using the methods of Grenander and Miller (1992), we can automatically scale, register, segment and label complex MR images, given existence of prior knowledge in the form of an electronic atlas or text-book.

Digital Electronic Atlas of the Brain

Electronic atlas of the brain is a valuable tool for co-localization, and can be applied to neuromorphometry. Both activities, co-localization and neuromorphometric analysis, are based on the availability of volumetric image data with a relatively large number of uniform voxel samples.

In general, past efforts toward the development of anatomic atlases have been limited to interactive generation of orthogonal planes from a volume for subjective display.

The registration of MR and PET imaging volumes to achieve a simultaneous display with overlap of functional areas, or linear mapping of sampled volumes into a pre-defined stereotactic space have been applied.

The principal limitations of electronic anatomic atlases involve the restriction to a high-n low resolution or low-n (often single sample) high resolution space. The registration of image volumes is often based on a landmark approach, with definition of homologous points (fiducials), computation of a rigid body transformation (and scaling) matrix, resampling of one volume into the coordinate space of the other.

The Atlas Matching Problem: Registration, Segmentation and Labeling

If an electronic brain atlas is available, its utility may be accessed by interactive expoloration of the sampled volume using computer graphics editing and rendering tools. Provided that the volume has been labeled, access to structures of interest may be accessed by selecting items of interest based on their names in an associated knowledge (data) base. If the data structures and information content of the knowledge base are sufficiently rich, one may access subvolumes of interest or interrogate the atlas based on anatomic nomenclature, functional and vascular territories, tissue class or other items of interest.

The process of matching a patient or normal control subject study to a pre-defined anatomic atlas is analogous, in many respects, to that employed in the comparison of two image volumes, from the same or different subjects. In general, the process consists of registration, segmentation, and labeling. Features are extracted from each volume and are matched to achieve a predefined degree of correspondence. This registration process is typically implemented by computing a simple global transformation matrix consisting of translation, rotation and scaling in 3 orthogonal directions. The rigid transformation is applied to one volume to match another by resampling each voxel in the new coordinate system. The resampling may be done by nearest neighbor, bi- or tri-linear interpolation or cubic convolution operations, depending upon the speed and degree of accuracy required. The volumes are placed into registration so that corresponding structures occupy the same (or nearly so) coordinate locations in both.

Segmentation of neuroimage volumes, especially from MR data sets, has been attempted using statistical image processing and pattern recognition techniques, especially supervised classification and unsupervised (cluster analysis) methods.

Labeling of neuroimage volumes to identify landmarks, functional regions, and vessels or other discrete structures is usually performed on segmented results.

Functional neuroimaging requires digital mapping of human brain anatomy, principally for co-localization of activation sites or for neuromorphometry. Mathematical/electrical-engineering researchers working in pattern theory and related fields have addressed the digital mapping of biological structure problem, and offer methods which provide important advantages over the rigid transformations or 2-dimensional analyses that are commonly available. These two groups - functional neuroscientists and applied engineering mathematicians- - are generally unaware of each others existence, and all groups would benefit from the exchange of ideas, problems and methodologies.

A major research program at Washington University in St. Louis led by Michael I. Miller of Electrical Engineering is based on construction of realistic and precise representation of medical and biological knowledge for real-world shapes and patterns. Common to their studies of biological and natural shapes to date: HANDS, XRAYS, LEAVES, MITOCHDONRIA, CELL MEMBRANES, TRACKS, and AMOEBA is the fact that while the shapes being imaged may be strongly structured, they are not rigid and therefore exhibit high variability. A fundamental task in the understanding and the analysis of biomedical scenes is construction of models that incorporate both variability and structure in a mathematically precise way.

There is no shortage of image processing algorithms - the literature abounds with computational techniques designed to improve pictures by noise suppression, or to recognize particular patterns so as to segment pictures into subpictures. Much of the greatest success to date has been in the modeling of sensor variability. For example, in computed tomography (CT), magnetic resonance imaging (MRI), and emission tomography (positron emission tomography (PET) and single photon emission computed tomography (SPECT)), the physical device electronics and optical characteristics are well understood.

Reconstruction algorithms abound which are highly tuned for accommodating sensor noise.

However, the variability type not in the sensor but in the shapes and biological structures themselves is much less well understood. Limitations of existing methodologies become visible for more ambitious tasks, where the goal is to arrive at a deeper understanding of the image ensemble itself. To make this possible, more subject matter knowledge must be built into the algorithms. If the algorithm is to make sense of a biological image, with all the possible variations, normal and abnormal, it must know something about the global anatomical structures themselves, and how they vary from one individual to another.

In other words, the methods must be model based, where the mathematical model are a precise representation of medical anatomical knowledge. But the enormous complexity of biological patterns, say contrasted with man-made manufactured objects, makes the design of representation a difficult, perhaps overwhelming endeavor. For example, in representing normal human brains, is it possible to design representations which represents the complexity of normal human anatomy, while accommodating human variation? Miller's research program rests on the belief that this can be done.

Global Pattern Theory

Since the mid-1970s researchers have built models that attempt to incorporate structure/variability at least for the simpler tasks. For example to achieve high quality restoration or segmentation, using probabilistic models such as Markov random fields (MRF), a good deal of success has been demonstrated. But this is not enough - what we have in mind is something more ambitious. The reason why textures can be dealt with using MRF models is that most (but not all) of their variability is of a very local nature: the probabilistic dependencies extend over quite a limited range. To meet the greater challenges global representations must be employed. Mathematical techniques for such representations began to appear in the early 1980s under the name of global shape models.

The global shape models attempt to represent image ensembles in terms of their typical structure via the construction of templates, and their variabilities by the definition of probabilistic transformations applied to the templates. It is not appropriate for us to describe in precise mathematical detail how this is achieved, or how the algorithms are implemented computationally. Simply stated, the transformations form groups (translation, scale, and rotation), and are applied so that while a rich family of shapes may be generated from a single template, the global properties of the templates are maintained.

Mathematical techniques are presented for the transformation of digital anatomical textbooks from the ideal to the individual, allowing for the representation of the variabilities manifest in normal human anatomies to develop (Miller et al., 1993). The ideal textbook is constructed on a fixed coordinate system to contain all of the information currently available about the physical properties of neuroanatomies. This information is obtained via sensor probes such as magnetic resonance, as well as computed axial and emission tomography, along with symbolic information such as white- and gray-matter tracts, nuclei, etc. Human variability associated with individuals is accommodated by defining probabilistic transformations on the textbook coordinate system, the transformations forming mathematical translation groups of high dimension. The ideal is applied to the individual patient by finding the transformation which is consistent with physical properties of deformable elastic solids and which brings the coordinate system of the textbook to that of the patient. Registration, segmentation, and fusion all result automatically because the textbook carries symbolic values as well as multisensor features.

Digital Anatomical Databases

The key to the global shape models is the construction of the templates and the variations which occur around them. In all of these projects the construction of the templates could be obtained with modest effort. For example, for MEMBRANES, MITOCHONDRIA, and AMOEBA they are all straightforwardly defined as

transformations of linear, elliptical and spherical shapes, respectively. The templates themselves are of low complexity.

Until recently this seemed to be the major obstacle for the successful application of the global shape models. The construction of digital anatomical libraries has recently been performed at several laboratories.

In particular, the "Visible Human" project undertaken by the National Library of Medicine (NLM) promises to yield results well suited to the definition of detailed anatomic templates. In the NLM Board of Regents report, it is noted that: "This Visible Human project would include digital images derived from computerized tomography, magnetic resonance imagery, and photographic images from cryosectioning of cadavers. A working group should be assembled from experts in anatomy, clinical imaging, and computer science to establish standards for recognition and computer representation of the data." Furthermore, "NLM should expand upon initial image libraries comprised of normal structure to encompass specialized image collections which represent structural informations, such as embryological development, normal and abnormal variations and disease-related images" (National Library of Medicine, 1990).

Advantages of Global Shape Models

Global shape modeling enables automatic registration, correspondence between slices, and noise suppression. This is useful in many functional neuroimaging applications. However, more important gains will result from the ability to achieve image understanding at a deeper level. As described in the Report of the NLM Board of Regents, the aims of their plan is not restricted to present libraries of image ensembles where each voxel means the observed intensity of the radiation observed by some sensor. The images will also carry symbolic values, say in the form of established names of anatomical regions, the type of tissue at a certain point, and functional or vascular territory.

The global shape models will carry such symbolic values, and will allow for the deformation of the coordinate system which the template library is defined on to be carried into the coordinate system of any given patient. If several sensors are used, fusion is automatically achieved when the global (and subsequent local) shape matching process is complete.

Cooperation between medical researchers building digital image libraries with mathematicians and engineers developing and implementing pattern theoretic algorithms is needed. It is a remarkable confluence in time that these plans in the collaborative biomedical community are developed simultaneously with the creation of pattern theoretic methodologies that require exactly the same empirical information that these electronic libraries will contain.

3-D CT/MR Image Segmentation

A requirement for image segmentation is present in almost all quantitative image processing applications. No general solution to this problem exists. There are numerous reports on ad hoc methods which suffice for specific narrowly defined applications. This remains as the principal obstacle to fully automated image interpretation and analysis, and is a central issue to current computer vision research.

Analysis of CT and MR tomographic volume imagery would be greatly facilitated if the objects within the volume could be presented in three-dimensionally (3-D) rendered views. The problem of image segmentation remains unsolved for the general case. One approach that circumvents this problem allows the human user to segment images interactively using morphology functions. This segmentation is performed concurrently with 3-D visualization providing direct visual feedback to guide the user in the segmentation process. Thus, rather than attempting to duplicate the complex and poorly understood human pattern recognition capability, our approach uses the human's own judgment and knowledge. The general feasibility of this approach using MR and CT images has been demonstrated. Massive data and computational requirements for interactive 3-D image processing often exceed current

processor limits, but the increased capacities of the next generation of computers are expected to make this approach practical (Hoehnė & Hanson, 1992).

SOLID MODELING

The synthesis of models from surface and volumetric data sets allows the creation of solid mathematical models from segmented data. These solid models are complete and unique, and have sufficient information to satisfy the requirement of any application where object geometry is needed. The representation of the model - whether boundary representation, cell decomposition, hierarchical, hybrid or other - can be translated to that needed for a specific application. The synthesis of models from biomedical data sets using shape-based and physically-based approaches is practical. These models are abstract mathematical representations that can be used to manufacture replicas through stereolithography or similar rapid prototyping technique.

In modeling three-dimensional (3-D) objects, the measurements that we have assumed are range data: for every point on the surface of an object, the x, y, z values in some coordinate system are known. Thus, a cloud of measured points is assumed. The question then is what are the geometric primitives that describe these measurements in the most coherent, succinct and yet natural way. This is an instance of the difficult, and generally unresolved, problem of segmentation in Computer Vision. In general, scene segmentation depends upon the task requirements. Hence, it is not possible to objectively segment an unknown scene in general.

This problem may be approached from two points of view:

1. if one assumes that the scene is unknown but the class of expected objects in the scene belong to a well defined geometric class of objects; and

2. if one assumes available an a priori pictorial database, as the anatomy atlas, which is used for matching the real patient data.

In the first case, the class of expected objects in the scene are superquadric volumes or objects that can be decomposed into superquadric primitives. The superquadric primitives are a class of parametric objects that are described by their position in the world, their orientation and two, so called, shape parameters. These two shape parameters allow us to model a continuum from a ellipsoid through a four sided parallelepiped. In a most natural way one can extend this class by adding more parameters, that is deformation parameters that model tapering and bending along the major axis. The issue is, however, that as one adds more parameters, the fitting procedure to the data becomes more and more unstable. This modeling is, in my opinion, well suited to model the gross shape of the human body but not the details. For more detailed modeling, one needs to invoke surface models, which we also have developed and experimented with. The surface models used in our work are initially first or second order. However, if the residuum is too large, higher polynomials must be invoked.

In the second case, a computerized anatomy atlas of the human brain and an elastic matcher was developed that takes this pictorial representation, i.e., the atlas, models it as a rubber sheet, and deforms it to the real patient data obtained via CT or MRI scans. This approach is in some way orthogonal to the previous approach. Here we assume that the measured data are from the human brain and that the measurements need to be explained in terms of the atlas. The adjustments are spatially local.

Rationale for Solid Modeling

Solid modeling systems allow users to create, store, and manipulate complete unambiguous models of solid objects, the results are:

Integration: one model has enough information to drive all applications

More applications can be addressed since more information is available

Improved automation: applications algorithms requiring less user assistance

Open-endedness: enough information to drive any future application (in principle).

Formal Properties of Representation Schemes

There are four properties of solid model mathematical representations schemes that determine their functionality and performance in applications. These include: 1)Domain, or coverage (What class of objects can be represented?), 2) Validity (Given a representation, is the corresponding object always a "legal" solid?), 4) Completeness (Given a representation, is the corresponding object uniquely determined?), and 4) Uniqueness (Given a solid, is there only one representation for it within the representation scheme?).

Informal Properties of Representation Schemes

Representation schemes have characteristics which determine their functionality in practical implementations. These informal properties of representation schemes include: Conciseness, Conversion Properties, and Effectiveness in applications.

Modeling Solids from Serial Sections

The automated synthesis of solid models from serial section images has been achieved by a method for creating unambiguous and complete boundary representation solid models with a hybrid polygonal/nonuniform rational B spline representation. Polygon surface approximation was applied to a sequence of parallel planar outlines of individual bone elements in the wrist. An automated technique for the transformation of edge contours into solid models was implemented. This was performed using a custom batch file command sequence generator coupled to a commercially available mechanical computer-aided design and engineering software system known as I-DEAS, produced by Structural Dynamics Research Corporation, Milford, Ohio. This transformation software allows the use of biomedical scan slice data with a comprehensive computer-aided design and engineering software system (Ho et al., 1992).

Shape-Based Modeling

A computational approach for the deformation analyses of problems in cell and developmental biology has been proposed. Cells and embryos are viewed mechanically as axisymmetric shell-like bodies containing a body of incompressible material. The analysis approach is based on the finite element method. It is comprised of three finite element ingredients: an axisymmetric shell/membrane element valid for modeling finite bending, shearing and stretching; a volume constraint algorithm for modeling membrane-bound incompressible material; and a contact algorithm for modeling the mechanical interactions between deformable bodies. These three ingredients can be applied to analyze mechanical experiments on cells. This same method was used to embryonic shape changes during development (Cheng, 1987).

Nonlinear shape distortions are considered as uncertainty in computer vision, robot vision, and pattern recognition. Shape restoration based on nonlinear two-dimensional (2-D) image shape transformation is used to approximate three-dimensional (3-D) deformations. Five particular image transformation models, bilinear, quadratic, cubic, biquadratic, and bicubic, were used for some special cases. Two general transformation models, Coons and Harmonic models, are used for more general and complex problems. These models are derived from finite-element theory and they can be used to approximate some nonlinear shape distortions under certain conditions. Furthermore, their inverse transformations can be used to remove nonlinear shape distortions. Some useful algorithms are developed. The performance of the proposed approach to nonlinear shape restoration has

been evaluated in several experiments (Tang & Suen, 1993).

Physical-Based Modeling

Physically-based modeling involves simulating the behavior of materials and objects using forces, torques, internal stress, energy, and other physical quantities. Materials such as rubber, cloth, paper, flexible metals, and the melting of solids into liquids have been successfully simulated using these techniques (Barr, 1987; Terzopoulos & Fleischer, 1988). Often the numerical solutions are coupled to a real-time graphical display where the deformable model can be observed in motion. For facial tissue the simplest physically-based model is a discrete spring lattice with node mass particles (Waters & Terzopoulos, 1990), while more complex models involve finite elements (Larrabee, 1986). It should be noted that when the observation of the model is an important consideration, physically-based techniques offer a significant computational advantage over more complex simulation solutions (Terzopoulos & Waters, 1993).

The union between *image synthesis* from Computer graphics and *image analysis* from Computer Vision describe the domain of Facial Synthesis, and it is physically-based algorithms that are common between the two fields. This paper briefly describes three examples where physically-based techniques can be effectively used in facial synthesis: model data reduction, a physical model of facial tissue, and the extraction of control parameters from human faces in motion. The underlying numerical solutions used in physically-based modeling are not presented in this paper; instead, references are supplied (Waters & Levergood, 1993).

Model Data Reduction

Constructing a compact geometric representation of the face is a non-trivial task, especially if the resulting geometry articulates. For images of the face it is best to concentrate nodes and polygons in articulate regions around the nose, eyes, and mouth (Waters & Terzopoulos, 1992).

A 3-D geometric surface can be constructed from CT data using *marching cubes* that converts an array of density data into a polygonal representation by sequential tessellation of a logical voxel constructed from eight pixels/site (Lorenson & Cline, 1987). Thresholds can isolate the bone and tissue densities in a volume thereby providing a geometric iso-surface for the bone and epidermal skin tissue. This algorithm typically produces in excess of 500 thousand polygons for a single iso-surface. Surface scanners, on the other hand, are regular in their sampling strategy, collecting data in ordered horizontal (radial) and vertical intervals, typically generating 512 by 256 samples (Rioux, 1985; Arridge et al., 1985; Vannier, 1991). Both the volumetric and surface scanned data result in oversampling in large flat regions and undersampling in areas of high curvature of the face (Waters, 1992).

Physically-based models can be used to re-sample the data by making observations about the scanned data set. The principle is one of mobile nodes observing sample sites and distributing themselves over the data given a finite set of observations. As with any physically-based lattice, nodes influence each other, modifying their neighbors position to some extent to maintain smooth coverage (Terzopoulos & Vasileseu, 1991). This is achieved by automatically modifying the spring parameters according to the observations on the nodes to which the springs are attached. The result is a non-uniform lattice reflecting the data under observation with a concentration of nodes in areas of high curvature and reduction in flat regions (Terzopoulos & Waters, 1993).

A Physical Model of Skin Tissue

Attempts to emulate muscle and skin deformations using physical models have proven promising (Waters & Terzopoulos, 1992). A simplified physical model combined with a parameteric muscle actuator (Waters, 1987), is capable of displaying a wide range of facial articulations (Waters, 1987; Terzopoulos & Waters, 1990). Furthermore, it is possible to simulate the model at high screen refresh rates on a graphics workstation (Waters & Terzopoulos, 1991).

A tri-layered model of facial tissue can be used as a first order approximation to facial tissue mechanics and can be constructed from surface scanned data by projecting sample nodes backward into the facial geometry (Waters & Terzopoulos, 1991). Complex composite units can then be constructed by allowing sample nodes to be chained together to create the building blocks of deformable surfaces and solids.

For the determination of material parameters, it is a common practice to extract specimens with well-defined geometries. The design of the samples and the choice of the applied load are meant to lead to a homogeneous stress and strain distribution in a part of the sample. When applied to biological materials, this raises a number of problems: homogeneous strains cannot be obtained because the materials have inhomogeneous properties, and the manufacturing of samples is hard or sometimes impossible (Lee, Terzopoulos, & Waters, 1993).

With the use of deformable templates to best match the data from some scanning source extensive prior information can be exploited when estimating the 3-D shape or image of the body (Terzopoulos & Fleischer, 1988; Amit et al., 1991).

The unsolved segmentation problem in Computer Vision arises since scene segmentation is highly task dependent. It is impossible to objectively segment an unknown scene, in general. Assuming that the scene is unknown but the class of expected objects in the scene belong to a well defined geometric class of objects. One can also use an a priori pictorial database such as an electronic anatomic atlas to match real patient data. Then the class of expected objects in the scene are primitives and are a class of parametric objects that are described by their position in the world, their orientation and two, so called shape parameters. Bajcsy and associates developed a computerized anatomy atlas of the human brain and an elastic matcher that takes this pictorial representation, i.e. the atlas, models it as a rubber sheet, and deforms it to the real patient data obtained via CT or MRI scans (Bajcsy, 1985).

Physically-based models can be effectively used for two converse problems: facial image synthesis and facial image analysis. For facial image synthesis, physical models facilitate the construction and articulation of faces acquired from volumetric CT/NMR and surface scanned data. For facial image analysis, physical models facilitate the extraction of time-varying control parameters from human faces in motion. Physically-based models can be effectively used in the construction of synthetic facial tissue from acquired data and are capable of emulating facial tissue dynamics. Furthermore, these models provide a valuable re-sampling strategy using elastic lattices and deformable templates. Physically-based deformable contours can effectively track nonrigid human facial motion.

3-D geometric surfaces can be constructed from CT data using marching cubes that convert an array of density data into a polygonal representation by sequential tessellation of a logical voxel constructed from eight pixels. A simplified physical model combined with a parametric muscle actuator is capable of displaying a wide range of facial articulations. A tri-layered model of facial tissue is used as a first order approximation to facial tissue mechanics and can be constructed from surface scanned data by projecting sample nodes backward into the facial geometry. Re-sampling is required to concentrate data in areas of high curvature and reduce data in flat regions. A deformable contour, called a snake, can track the nonrigid motion of salient facial features, such as the mouth and eyebrows over successive frames (Kass et al., 1988).

We seek to construct a realistic and precise representation of medical and biological knowledge for real-world shapes and patterns. Shapes being imaged may be strongly structured. They are not rigid and, therefore, exhibit high variability. A fundamental task in the understanding and the analysis of biomedical scenes is construction of models that incorporate both variability and structure in a mathematically precise way. How can we design representations which incorporate the complexity of normal human anatomy, while accommodating human variation? Global

shape models attempt to represent image ensembles in terms of their typical structure via the construction of templates, and their variabilities by the definition of probabilistic transformations applied to the templates. The global shape modeling enables one to automatically carry out registration (correspondence) between slices, and noise suppression (Grenander, 1994).

Automated analysis to organize, integrate, quantify and interpret 3-D anthropometric data sets are required. This translates to a need for reliable and meaningful segmentation, integration of multisensor information, approaches to dealing with large amounts of image and knowledge-source data, and inference of dynamic characteristics from time-sequential imagery. Manifold representations of 3-D data study of higher-dimensional multi-sensor data requires an integrating representational formalism. Computing on 3-D and higher dimensional manifold representations shows promise of providing this integrating formalism (Grenander & Miller, 1992).

A digital image-based technique was developed for the measurement of nonhomogeneous strain distributions, finite element modeling and the use of a minimum-variance estimator. The method is tested by means of experiments on an orthotropic elastic membrane of woven and calendered textiles. Five parameters are identified using the experimental data of a single experiment (Oomens et al., 1993).

A physical-based modeling methodology has been developed for the computer synthesis of realistic faces capable of expressive articulations. A sophisticated three-dimensional model of the human face was developed that incorporates a physical model of facial tissue with an anatomical model of facial muscles. The tissue and muscle models are generic, in that their structures are independent of specific facial geometries. To synthesize specific faces, these models are automatically mapped onto geometrically accurate polygonal facial representations constructed by photogrammetry of stereo facial images or by non-uniform meshing of detailed facial topographies acquired by using range sensors. The methodology offers superior realism by utilizing physical modeling to emulate complex tissue deformations in response to coordinated facial muscle activity. To provide realistic muscle actions to the face model, a performance driven animation technique is developed which estimates the dynamic contractions of a performer's facial muscles from video imagery (Waters & Terzopoulos, 1992).

The analysis of dynamic facial images for estimating and resynthesizing dynamic facial expressions has been accomplished using physical-based modeling. The approach exploits a sophisticated generative model of the human face originally developed for realistic facial animation. The face model, which may be simulated and rendered at interactive rates on a graphics workstation, incorporates a physics-based synthetic facial tissue and a set of anatomically motivated facial muscle actuators. Dynamic facial muscle contractions are estimated from video sequences of expressive human faces. An estimation technique that uses deformable contour models (snakes) to track the nonrigid motions of facial features in video images was developed. The technique estimates muscle actuator controls with sufficient accuracy to permit the face model to resynthesize transient expressions (Terzopoulos & Waters, 1993; Kass et al., 1988).

SYNTHESIS OF SPACE FILLING REPLICAS FROM SCANNED OBJECTS

Rapid prototyping or data driven manufacturing systems are being used to make hard prototypes from CAD data today. There are four technologies used for rapid prototyping (conversion of three dimensional images to hard prototypes): Photopolymer, Powder Sintering, Lamination, and Free Form Fabrication. These are each described below.

- **Photopolymer** techniques rely on families of resins that polymerize from a liquid to a solid when exposed to light. In the most common system (3-D Systems, Inc.) the three

dimensional solid data is converted into a sequence of constant thickness layers. Each layer only requires two dimensional information to be recreated. The three dimensional form is recaptured by sequentially tracing out the two dimensional layer information with a laser beam on the surface of a vat of photoresin. The surface is, of course, recoated and repositioned as each layer is completed. A competing system (CUBITAL, Inc.) uses an erasable toner photomask and an ultra-violet flashlamp to image each layer.

- **Powder sintering** schemes also use a sequential layer process, but with finely ground powders. These powders are bound to solid form by melting or sintering with a laser (DTM Corp.) or an ink jet directed binder material (3-D Printing). Commercial materials include ABS plastic, polycarbonate, nylon, and investment casting wax. Processes for ceramics and metals are under development.

- **Lamination** processes (Helisys and Landfoam) build up layered solids from thin sheets of paper, metal, or foam board. These machines automate laser cutting, registration, and thermal lamination processes.

- **Free form fabrication** tools automate several material deposition techniques. The earliest (Babcock and Wilcox) of these used a robot arm to direct a welding rod to build up complex three dimensional geometries such as pipe fittings and valve bodies in difficult to fabricate steel alloys. A more recent entry to the field (Stratasys) is essentially a filament fed "hot glue gun" that deposits thermoplastic materials in layers.

Each of these tools allows physically realistic simulations of three dimensional forms. Specified material properties can sometimes be directly achieved or can be created via replication techniques. Geometric resolution and accuracy is usually better than 0.25 mm and generally exceeds the accuracies of scanners presently in use for human body scanning.

The principal advantage of these tools is that extremely complex geometries can be produced (curvatures, detailed features, internal cavities, etc.) within a few hours of CAD solid mathematical solid model generation. Furthermore, it should be possible to develop direct routes from scanned data points to hard objects.

The display of three-dimensional anatomy with stereolithographic models has been demonstrated. Stereolithography, a new technique of prototype fabrication developed for the discrete manufacturing industry, offers an alternative means to display patient anatomy. Like current computer aided design (CAD) systems, digital image data from computed tomography (CT) and magnetic resonance (MR) are used to produce a physical model. Unlike conventional CAD/CAM, a cutting tool is not used and toolpath limitations do not exist. Stereolithography uses an ultraviolet laser to selectively polymerize and solidify a polymeric liquid plastic solution under computer control. The device was used to produce a model of cranial bony anatomy from CT image data, providing full internal detail in the constructed model, including encased sinuses, foramina, and potentially complete internal anatomy within a closed skull (Mankovich et al., 1990).

RAPID APPLICATIONS SOFTWARE PROTOTYPING

Software development systems operating at a very high level with traditional command languages, and most recently point-and-click interfaces such as the PV Wave and IDL products have revolutionized software development for many research groups. Data flow languages such as that incorporated in the "ApE" Animation Program Executive from the Ohio Supercomputer Center or Imaging Workbench by Paragon Imaging are object oriented graphical user interfaces used for building interactive applications. This software and many related systems are available on the Internet via anonymous ftp transfers, greatly facilitated by the recently developed Mosaic software interface available from the U.S. National Center for Supercomputer Applications at the University of Illinois-Champaign/Urbana (ftp site is ftp.ncsa.uiuc.edu or via URL file://ftp.ncsa.uiuc.edu). AVS or Applications Visualization System, Khoros, and SGI Explorer are examples of data flow language-based rapid applications software prototyping systems.

MATLAB, Gauss, and Mathematica are mathematical software systems that serve to integrate requirements in symbolic algebraic manipulation, numerical analysis, and display using a notebook paradigm. At higher levels of abstraction, they provide support for applied mathematical analysis.

REQUIREMENTS OF 3-D ANTHROPOMETRY SOFTWARE - SUMMARY

Basic functionality for visualization, retrieval, and analysis of 3-D anthropometry systems are recognized. In a basic implementation, 3-D anthropometric data from a national or international survey is available on CD-ROM disks or via an interactive network. The user, who may not be skilled in the details of anthropometric measurement methods, procedures or technology, should be able to extract the relevant parameters needed to satisfy design or procurement requirements from a defined population at a suitable interactive graphical workstation. The basic software system should make the required information available after the user has formulated a query with an intuitive man-machine interface tailored to 3-D anthropomteric applications. This may take the form of menus, icons, or simple command sequences. Results are displayed on the workstation screen in graphical visualizations and tabular form that may be printed in hardcopy or transferred electronically to other application programs such as CAD/CAM software, spreadsheets, and word processors.

Higher functionality can be provided when the application warrants it, including computation of fit after matching a pre-defined manufactured mechanical object to the subject population, interrogation of population variability and size range, comparison of reference populations to one another or to selected individuals or environments, finite element analysis of deformable object and many others. There are few limits imposed by modern software development systems that emphasize portable, reusable, and extensible applications development.

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CHAPTER V: DATA MANAGEMENT AND COMMUNICATION

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INTRODUCTION

Unlike anthropometry data of five to ten years ago, modern 3-D surface anthropometry data is a complex set of multimedia data consisting of text, graphics, images, and may eventually include audio and video data as well. The management of this complex and extensive set of data requires a fully integrated information management system that has the capability to rapidly store, relate, interrogate, access, visualize, manipulate, and analyze this complex set of data. This information system must also be a flexible and dynamic system in that both changes to the data and data structure can be accommodated in a straight forward and expeditious manner. Modern data base management information system (DBMS) provide the features desired in comprehensive 3-D anthropometric data base. This chapter will examine the available DBMS methodologies and provide recommendations for which approach is best for managing 3-D anthropometric data.

Modern DBMSs are generally distributed databases, meaning multiple users have on-line access to the database via a computer network. Many communications technologies currently exist and are being used to integrate multiple users into a distributed database system. Database developers at the Computerized Anthropometric Research and Design (CARD) Laboratory at Wright-Patterson Air Force Base in Dayton, Ohio are now working on an anthropometric database that will be accessible to users around the world.

The second section of Chapter V will examine the current communications technology in use as well as potential upcoming technologies to meet the demands of multi-media distributed databases. The final section of Chapter V will concentrate on picture archiving and communication systems (PACS). The PACS review is included as it addresses many of the same issues relative to 3-D anthropometric image data.

DATA MANAGEMENT REVIEW

Managing Information Effectively

The basic problem of information management is not one of storage. Virtually any kind of information can easily be stored in a computer file and retrieved. The simplest and most common type of computer file, called a "flat file," is one in which the file's contents are not related or linked to other files. Storing data in a flat file is often the best approach for data containing simple relationships, and for data that does not need to be shared among users.

Unfortunately, flat files are not very efficient for sharing information, or for storing complex data. Without mechanisms for structuring information, controlling simultaneous access, and maintaining security, flat files can easily lead to inconsistent results or corrupted data. A historical example of an anthropometric flat-file database is the AMRL Data Bank Library (Churchill et al., 1977).

The Purpose of a Database

The solution to these problems is the DataBase Management System (DBMS). A Database Management System consists of a collection of interrelated data and a set of programs to access that data. The collection of data, usually referred to as the database, contains information about one particular enterprise. The primary goal of a DBMS is to provide an environment that is both convenient and efficient to use in retrieving and storing database information.

Database systems are designed to manage large bodies of information. The management of data involves both the definition of structures for the storage of information and the provision of mechanisms for the manipulation of information. In addition, the DBMS must provide for the safety of the information stored, despite system crashes or attempts at unauthorized access. The DBMS itself does not necessarily provide the capability to do data analysis, manipulation and

visualization, but facilitates these processes by managing the data. An early example of an anthropometric database is the CARD Laboratory's on-line database (Robinson et al., 1992).

Examples of Databases

There are many databases currently in use within scope of anthropometry. Demographic data is one type, human system integration data or fit test data another, equipment geometry, such as a cockpit layout a third. Fit data entities might be variables such as comfort score, a center of gravity location, or a stability measure. For medical applications, in addition to images, demographic information and other types of patient records on a subject or a research population is usually represented by means of text and graphics. Each of these are data entities that must be accessible along with the 3-D anthropometry.

In other words, within a hospital, CT, MRI, X-ray, other image data, patient history, medication records, and prognostic comments are often evaluated together to diagnose a problem. Similarly, for designing a helmet there is a need to examine the fit scores, subject demographic data such as age, occupation etc. in addition to the scanned data of the human and helmeted surfaces.

Before any data base is built it is necessary to establish what types of data "entities" there are and how they should relate to each other within the data base. It is also necessary to plan how users will enter into and navigate through the data base. There may be many different accessing and interrogation pathways depending upon the application and it will be important to pre-determine this as much as possible to ensure that the final system functions properly.

Finally, there is often a need to move data, displays, or analysis results from one location to another. This may be as close as another room within the same facility or to another facility in another country. Networking systems and hardware availability place practical limits on the data that can be used locally versus long distance.

For the purpose of this report, storing, relating, and navigating through the data base design are considered to be "data management" issues. Moving information or linking one data base to others is referred to as "communication." Data bases which combine the archiving and communication of electronic images and other types of data are commonly referred to in the literature as "PACS" or Picture Archiving and Communications Systems. Background on methods and tools first for archiving and then for communication is provided below, followed by an overview of PACS currently in use or in development.

Evolution of Database Systems

Ullman (1989) defines three kinds of database needs:

- Data Management is concerned with simple data structures and operations, such as those required by traditional business applications. Relational DBMSs, with tabular data structures of integers, strings, and other simple data, address the needs of data management.

- Object Management is concerned with more complex data structures, such as those required to represent the parts of a document, program, or design.

- Knowledge Management is concerned with maintaining complex rule bases, used to derive information about a domain through an inference system. These logic databases are descended from theorem-proving systems developed with research on artificial intelligence.

These three kinds of database capabilities can be regarded as a progressive evolution of database systems to support more complex applications.

Evolution of Database Structure

Of all the problems that DBMS address, the most challenging has been developing a mechanism for representing data structure. In fact, the evolution of databases over the past thirty years consists primarily of developing new generations of technology to better represent the structure of real-world information.

<u>Early Database Programs</u>

It is important to remember that data base systems are designed for one purpose: to simplify the development of data-intensive applications. The earliest data base programs interacted directly with storage devices with each program having its own file model and manipulation operators. Database systems of the 1950s (first generation) accessed data from a secondary storage device such as punch cards or magnetic tape. This mode of access limited the system

to sequential processing of file records only. Database systems (second generation) of the 1960s capitalized on the emergence of magnetic disks as a "fast" secondary memory which led to more sophisticated file systems. These file systems made it possible to directly access file records via its address on disk without having to read all the records physically located in front of the desired record. The more advanced file systems of second generation databases also made it possible to perform multiple access of files (Vossen, 1991).

An example of the second generation file system was the indexed sequential access method (ISAM) that replaced the program specific models with standardized access methods. An ISAM file can be accessed in two fundamentally different ways; sequentially or via a separate primary-key index (Litton, 1987). The ISAM file system was the precursor to the database management information system (DBMS) and provided the most basic features of modern DBMSs (Cattell, 1994). Specific characteristics of the ISAM file system included:

- Fixed-length records with data fields of various types

- The ability to store the records in a disk file, to deal with more data than can fit into memory, and to provide a persistent storage medium for them.

- Indexes including hash indexes and more recently B-trees to quickly locate records satisfying constraints on field values.

- File and record locking to control concurrent access.

<u>Database Management Systems (DBMS)</u>

DBMSs represented the next stage in database evolution and were characterized by the introduction of the distinction between logical and physical information, which occurred parallel to an increasing need to manage large collections of data as opposed to computational processing of data. These systems sit on top of the access method software interfacing with programs in a hardware-independent manner. These database systems were classified as third generation systems.

Early DBMS

The earliest forms of DBMSs surfaced in the 1970s in the way of the hierarchical and network models. A Hierarchical DBMS is a general level model that stores data in hierarchies of record types. The main disadvantage of the hierarchical model is that information doesn't always follow a set hierarchical pattern. Network DBMS attempted to compensate for this deficiency by allowing all possible connections among data entries. This in effect permitted any possible information structure to be represented.

Data in the hierarchical and network models are represented by collections of records and relationships among data represented by links, which can be viewed as pointers. The records in these models are organized as a collection of graphs (Korth & Sliberschatz, 1991). In a hierarchical model, the graph has the form of a tree where the record types are the nodes of a tree and the nodes are connected by arcs denoting parent-child relationships. In a network model, the nodes in the graph are record types and the arcs between nodes indicate relationships. Unlike the hierarchical databases, network databases are not restricted. This means that a given node can have more than one arc, each for a different relationship. There is no mapping restriction among pairs of nodes on an arc, unlike hierarchical databases where there is only one arc between nodes (Ozkaharan, 1990). Capabilities of the hierarchical and network databases include the following:

- Record identifiers and link fields used to connect records together

- Multiple indexed files that can be opened simultaneously, treated as a single data base

- Transactions to provide automatic crash recovery, deadlock detection, and data base consistency with multiple users.

The main advantage of both the hierarchical and network data base models is that data is presented to users in a form that reflects the natural structure of real-world information. Since the natural structure of the real-world information is incorporated directly in the data base structure, access to the data is generally very fast. Unfortunately, hierarchical and network model structures are very constrained in that the data must follow a single information structure. Attempts to access data outside of the built-in-structure is very

difficult, painstakingly slow, and typically requires substantial programming.

Relational DBMS

The next generation (fourth generation) in the database evolution occurred in the 1980s with the emergence of relational DBMSs (RDBMS). Relational databases presented a higher level of abstraction by virtually eliminating the need for navigation. RDBMS are more flexible than their predecessors in that they store only the lowest-level associations directly in the database. Application programs are used to reconstruct the higher-level structures by reconnecting the low-level associations. Different application programs can be used to extract different high-level structures which is the key to the RDBMS flexibility. However, this flexibility does not come without a cost. The time to reconstruct complex high-level structures slows down the access time. Application programs also become more complex since each program has to contain the code to perform the reconstruction of higher-level structures (Taylor, 1992).

The major strengths of the relational approach is that data can be accessed in a very flexible manner, which is not the case with its predecessors, the hierarchical and network models. The relational model represents data and relationships among data by a collection of tables, each of which has a number of columns with unique names. This approach is the RDBMS' major strength in that data access and manipulation is almost completely separated from the program code. In addition, storage of data is also invisible to the user. This means the way data is physically or logically stored can be changed without changing the application programs. Using high-level query language such as Structured Query Language (SQL), it is possible to specify which data is required without specifying how the data should be accessed. This makes the application programmer's job somewhat simpler. The ability to access data without specifying how the data is to be accessed marked the transition from a record-oriented to a set-oriented methodology of managing and processing data.

Work is currently underway to develop the next generation or fifth generation of database systems. Concepts being explored include extensible systems, logic-oriented systems, and object-oriented systems. One promising approach, Object Oriented DBMS (OODBMS), is the methodology adopted by the CARD Lab for the management of their 3-D anthropometric data. Details of the object-oriented approach are provided in the following paragraphs.

Object DBMS

Now in the 1990s, a new breed of management systems are evolving, the Object DBMS (ODBMS). ODBMSs, based on object-oriented data models originated with the object-oriented programming paradigm. The object-oriented programming paradigm subsumes the concept of abstract data types in programming languages (Micallef, 1988). Abstract data-type definitions explicitly define a public and private portion of a data structure, or object.

So, what is an object? Objects are real-world or abstract entities that we model in software. They might be documents, airplane parts, transistors, people, scientific hypotheses, or chemical formulae. An object is a black box that can be constructed and modified, independently of the rest of the system, as long as its public interface definitions are not changed. All database applications deal with objects in some sense. In the case of our application, however, the objects are more complex and take a more central role in the application.

Conclusions

The advent of object-oriented software offers new solutions to the classic problems of building large-scale, complex software systems and specifically information systems. The structural properties of complex objects alone necessitate the new ODBM technology. Given the inherently complex nature of medical data in general, ODBMS systems will create a new generation of applications that more closely model their respective real-world entities.

Anthropometric databases have, in the past, been one of two types: flat-file, dictionary-like or relational, survey-oriented. Obvious limitations exist with the flat-file information system. Although inexpensive to create, the benefits of data distribution, concurrency, and data integrity quickly redirect attention towards more reliable and flexible systems. Relational database systems were the next logical step in the evolution of information systems. One example, the CARD Database, allows users to query and generate statistics across survey and population boundaries. For users and researchers alike, this was a wealth of information that could be accessed and studied at one site.

Users of information systems are being exposed daily to the large amounts of information available from their desktop, and the more information one gets, the more one needs. Users are repeatedly shown the flexibility and availability of information from various sources. With the communication revolution underway, every source of information that will survive the siege will undergo a major reconstruction.

The communication revolution is happening everywhere: media, telecommunication, marketing and retail - information construction is underway. One key element will be resource distribution. Costs will preclude the total reconstruction of information systems. The optimal path will be to utilize legacy data, while taking steps to implement robust systems to handle the complexity of data that is now being demanded. Business units must utilize various sources of information to build an empire. For many the information exists, in various forms, and in various locations. Success will be defined on how well existing data banks can be used and brought into the revolution.

Within the anthropometric community, there is no better analogy. In fact, most of the existing information that we rely on can never be recreated. Fore example there is no longer a chance to measure a 24 year old Air Force captain in 1969, that chance is gone, forever. Access to distributed data is the key component to anthropometric research of the future. Constrained funding will limit duplicate surveys by various institutions or governments. This supports a cooperative effort to (coordinate) the distributed resources that are available, world-wide.

Additionally, as requirements expand for new uses of anthropometry, existing systems will be fully burdened. The anthropometric data and collaborating information existing in yesterday's relational systems will be stretched beyond it's capabilities. Object-oriented information systems will provide the longevity and expandability necessary to survive the information explosion. More notably, Object-Oriented Database Management Systems are evolving to a maturity level that they can now be considered serious contenders for the storage of multi-dimensional information.

DATA COMMUNICATIONS REVIEW

Data communications is evolving rapidly and revolutionizing how we do business in the office, industry, academia and the hospital. The ability to transfer data between computers in a reliable and efficient manner has contributed to enhancing office and factory automation, collaboration from remote sites, and patient management. As a result, numerous strategies for data communication have been developed.

This section will review the types of networks available to facilitate data communication between computers, the currently available media with which to transmit the data, and the options for organizing or formatting the data. Applications of data communications include facilitating access to the human 3-D anthropometric data proposed by this working group to be collected. The ARCHIVING REVIEW describes possible implementation strategies for a 3-D anthropometric database consisting of image and text data. This is similar to the picture archiving and communication systems (PACS) hospitals are currently implementing. This is reviewed in the next section, CURRENT PACS REVIEW. For this database to be of practical use, efficient data communication technology will need to be connected to the database to allow users to interact with the database.

Computer Networks

A computer network is a collection of computers interconnected with one or more of the data communication media described below. This connection allows data to be transferred between computers located at nearby or distant sites. In this section, the important features of computer networks will be presented.

Network Structure

Any computer network consists of a collection of machines which are intended to run user application programs connected together by a communication **subnet**. These machines are usually computers or computer terminals and are called **hosts** or end systems. The user interface program to the 3-D anthropometry database this working group is proposing is an example application program. The communication subnet transfers data within **messages** from host to host and consists of transmission lines connected by switching elements. The transmissions lines can also be called **channels**, circuits, or trunks and are one or more of the types of data communications media described below used to carry bits of data. The switching elements are termed Interface Message Processors (**IMPs**), packet switch

nodes, intermediate systems, or data switching exchanges. IMPs are specialized computers which accept an incoming message from one channel and decide on which channel to output the message. Figure 5-1 from Tanenbaum (1989) shows the relationship between hosts and the subnet. Note that more than one host may be connected to the same IMP (Tanenbaum, 1989).

Point-to-point vs. Broadcasting

There are two general ways to connect the IMPs: **point-to-point** channels or a **broadcast** channel. A subnet point, store-and-forward or packet-switched using point-to-point channels can be called a point-to-subnet, each of which describe an important point about point-to-point subnets. First, each IMP in a point-to-point subnets can be considered a point which has a direct channel connecting it to at least one other IMP or point in the subnet. Obviously, this results in many ways in which the IMPs can be connected. Figure 5-2 from Tanenbaum includes some of these possible topologies. This results in a network containing numerous channels, and if two IMPs do not have a direct connection, then they must send messages through another (possibly many other) IMP(s) which do have direct connections. Second, while an IMP waits for an open channel to send the message to the next IMP, it must initially store the message before forwarding it to the next IMP. Finally, since messages can also be called packets, the IMPs can basically be considered elements which switch a packet from one IMP to another in order to route a packet from one host to another (Tanenbaum, 1989).

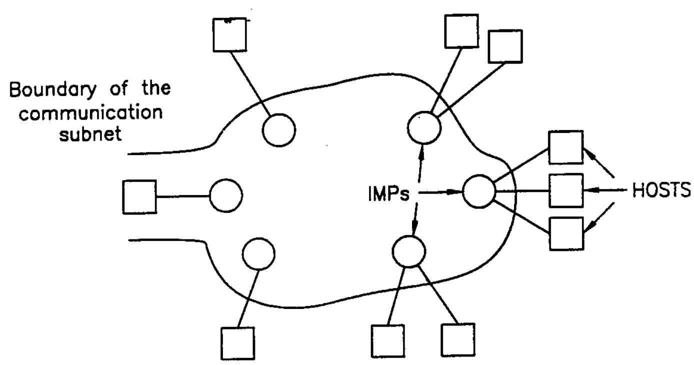

Figure 5-1. Relation between hosts and the subnet.

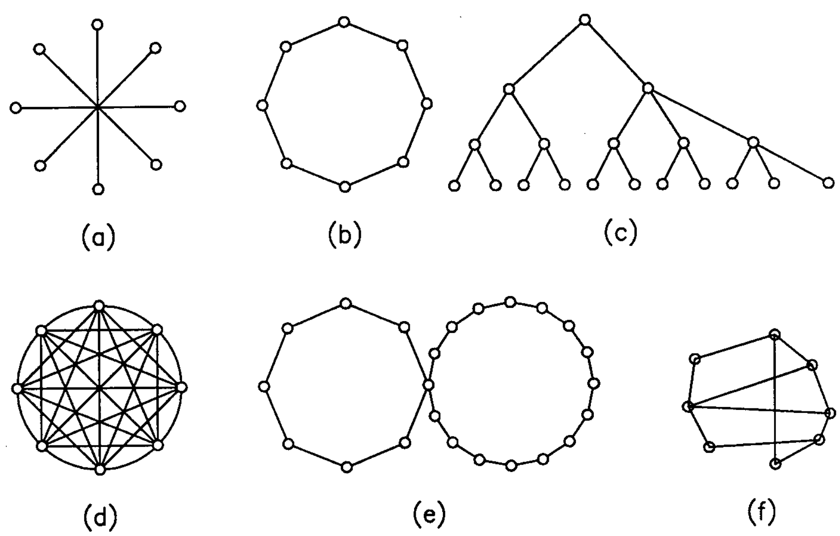

Figure 5-2. Some possible topologies for a point-to-point subnet. (a) Star, (b) Ring, (c) Tree, (d) Complete, (e) Intersecting Rings, (f) Irregular

Conversely, a broadcasting subnet consists of IMPs connected by a single broadcast channel. In this type of network, each time a packet is sent on the subnet by an IMP, it is available to all other IMPs. This may be desirable for a bulletin board message, but undesirable for more personal messages. This can be resolved by including the destination address within the packet. Now, when a machine receives a packet, it only accepts those packets addressed to it and ignores all others. Some of the topologies for broadcasting subnets are shown in Figure 5-3 from Tanenbaum.

ISO-OSI Reference Model

For an application program running in one host to transfer data through a network to an application program running in another host, there are many things that need to be done. In order to simplify and standardize the process, the International Standards Organization (ISO) divided the process into seven steps defined by its Open Systems Interconnection (OSI) Reference Model. The ISO-OSI Reference Model consists of seven layers each with certain responsibilities. Each layer builds on the services provided by all layers below it. Although ISO has developed standards for each layer also, the OSI model itself does not specify how each layer of the network should perform its tasks, but only tells which layer should perform each task required of the network to transfer data between hosts. Many of the more recent computer networks have been developed in compliance with the OSI model (Beauchamp, 1990; Guy, 1992; Tanenbaum, 1989).

A diagram of the ISO-OSI seven layer model is shown in Figure 5-4 from Beauchamp. The physical layer is concerned with transmitting a bit stream over a channel by standardizing network connectors and their electrical properties. The data link layer ensures the data transmitted is error-free when passed to the network layer, which takes care of routing messages through the network. The lower three layers can be grouped and called the communication-oriented layers. The transport layer is the first host-to-host interaction, while the previous three layers consisted of host-to-IMP, IMP-IMP, and IMP-host interactions. As such, the transport layer ensures that reliable data transfer has occurred from one host to another. It can be viewed as a bridge between the lower communication-oriented layers and the upper application-oriented layers. The session layer can be very thin and tends to enhance the services provided by the transport layer by establishing, controlling, and terminating dialog between the application programs running on the hosts. The presentation layer organizes the data into the format or structure required by the application program to interact with the data. The application layer contains protocols that are commonly needed by application programs, like file transfer, terminal emulation and electronic mail (Beauchamp, 1990; Guy, 1992; Tanenbaum, 1989).

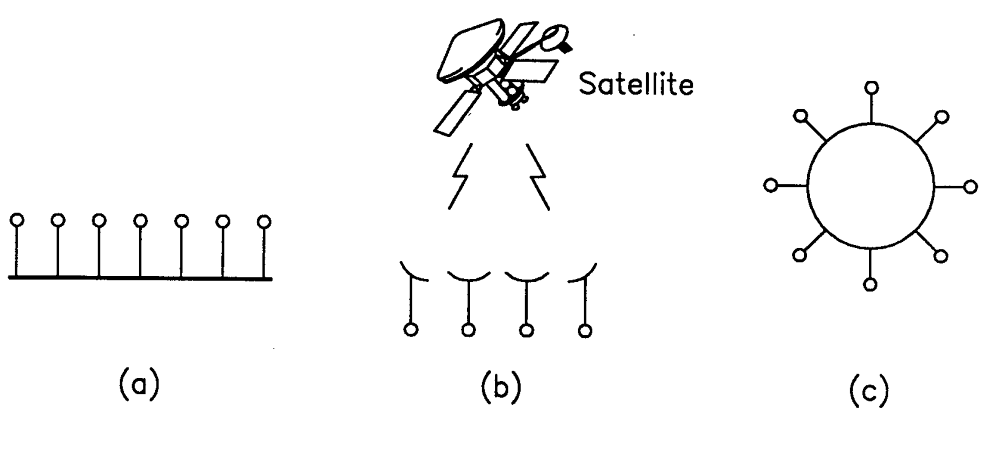

Figure 5-3. Communication subnets using broadcasting. (a) Bus, (b) Satellite or radio, (c) Ring

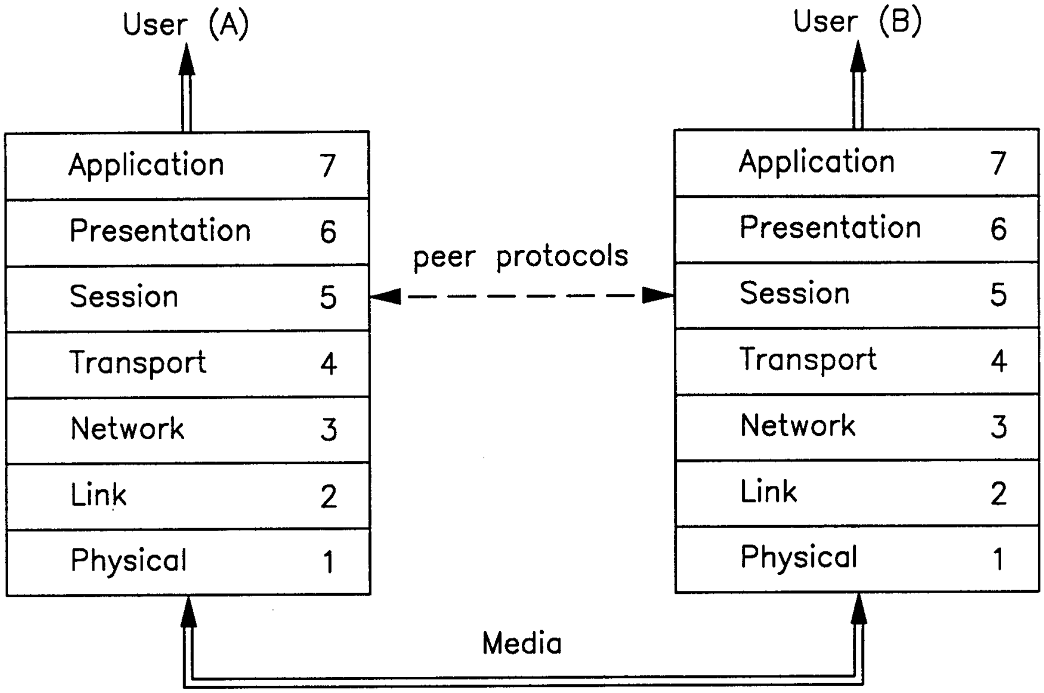

Figure 5-4. ISO Seven-layer communications model.

Introduction to LANs, MANs and WANs

Local Area Networks (LANs), Metropolitan Area Networks (MANs) and Wide Area Networks (WANs) are generally distinguished by the distance between hosts connected by the network. The hosts of a LAN are usually confined to a few kilometers (km) in diameter, while the hosts of a MAN can cover an entire city in the few tens of km range. WANs consist of hosts spaced even further away and can also be called long haul networks. LANs are also generally owned by a single organization and have a total data rate greater than a few megabits per second (Mbps). WANs, on the other hand, tend to be owned by many organizations (e.g., a common carrier owning the communications subnet and multiple companies owning the hosts) and have data rates less than 1 Mbps. Nearly all LANs use a broadcast communication subnet, while nearly all WANs use a point-to-point subnet. The few LANs that use point-to-point subnets tend to use a symmetrical topology, while point-to-point WANs tend to use an irregular topology. In a broadcast LAN, the IMPs tend to be reduced to an interface card embedded in each host so that there is a single host for each IMP. In contrast, the existing broadcast WANs tend to have multiple hosts connected to the same IMP and be based on communication satellites. MANs are more similar to LANs and tend to use fiber optic based LAN technology to connect a company like a bank with branches spread out over an entire city (Beauchamp, 1990; Tanenbaum, 1989).

Logical ring LAN to be wired like a star so that any problems with a particular section of the ring can be isolated without a massive rewiring exercise. Since the IMP tends to be embedded in the host for LANs, this host/IMP combination will simply be referred to as a node of the network (Guy, 1992).

In a star LAN each node is connected by a point-to-point channel to a central control node. The central through the network. There are no true star LAN standards, so vendors have developed their own protocols reducing the compatibility of these LANs between vendors. In a ring LAN, the nodes are directly connected by point-to point channels, and

transmitted messages travel from one node to the next in one direction around the ring. Ring LANs usually use a token passing protocol as described below to route messages through the network. The Institute of Electrical and Electronics Engineers (IEEE), which has produced the generally accepted LAN standards, describes the LAN token ring in IEEE Standard 802.5 . A bus LAN is a broadcast system in which the nodes share a common data communication medium. The two common types of bus LANs are distinguished by the way in which this medium is accessed in order to route messages through the network. IEEE Standard 802.4 describes the LAN token bus, and IEEE Standard 802.3 describes the LAN Carrier Sense Multiple Access/Collision Detection (CSMA/CD) bus. Token passing and CSMA/CD are described below. A tree is just a generalization of a bus in which the channel branches at either or both ends; however, a tree offers only one transmission path between any two nodes. The branches coming off either end of the bus never link up (Guy, 1992; Tanenbaum, 1989).

The ISO-OSI Reference Model described above also applies to LANs; however, since LANs are primarily concerned with the transmission of information over a physical medium, only the first three levels are usually discussed. Level one, the physical level, consists of an interface card (which serves as the IMP) connected to the communications medium. Level two, the data link layer, tends to be divided into two sub-layers: the medium access sub-layer and the logical link sub-layer (Guy, 1992; Tanenbaum, 1989).

The Medium access sub-layer is directly above the physical layer and is commonly described by IEEE 802.3 - 802.5. IEEE 802.3 (CSMA/CD) is associated with a bus topology in which each node has the ability to detect traffic on the channel (Carrier Sense) and will not transmit when traffic is detected. In addition, any node can send a message on the channel once it senses that the channel is free (Multiple Access). However, since there are propagation delays of messages across the network, two nodes may sense that the channel is free at the same time and begin transmitting simultaneously. This will cause a collision resulting in corruption of the messages. Since each transmitting node also has the ability to detect the message it is sending, when a corrupted message is detected, a collision is identified (Collision Detect), and the current transmission is aborted. The node then waits until the channel is free and tries to send the message again. Algorithms to determine the amount of time to wait to retransmit can be employed to decrease the likelihood of a subsequent collision. IEEE 802.4 and 802.5 both use a token passing protocol to route messages through the LAN in which they are associated, bus and ring, respectively. Tokens are special bit patterns that travel through the LAN when there is no message traffic. Possession of the token gives a node exclusive access to the LAN for transmitting its message eliminating the possibility of a collision (Guy, 1992).

The logical link sub-layer is described by IEEE 802.2 and provides a common format for Logical Link Control (LLC) so that LANs using different medium access sub-layers can be interconnected. Directly above the logical link sub-layer is ISO-OSI layer three, the network layer. The network layer is described by IEEE 802.1, which is an attempt to integrate LAN technologies into the wider world of networking by providing an overall framework and a consistent interface to the lower levels. Figure 5-5 from Guy diagramatically illustrates the relationship of ISO-OSI layers 1 - 3 to IEEE 802.1 - 802.5 (Guy, 1992; Tanenbaum, 1989).

Since Ethernet is such a common LAN, it will be briefly discussed. Ethernet uses CSMA/CD protocol and formed the basis for IEEE 802.3. Xerox Corporation , Digital Equipment Corporation, and Intel Corporation developed a standard Ethernet with a 10 Mbps data transmission rate. Its topology is tree shaped composed of separate bus segments, and the medium is baseband coaxial cable. Baseband coaxial cable is described in the Data Communications Media section below. The maximum cable length is 500 m, the maximum distance between nodes is 2.5 km, and the maximum number of nodes is 1024 (Beauchamp, 1990; Guy, 1992).

The three 802 LANs discussed above are all based on copper media. However, fiber optics is becoming increasingly important, not only for wide-area point-to-point channels, but also for MANs and LANs. The general characteristics of fiber optic cables are discussed in the Data Communications Media section below. Fiber Distributed Data Interface (FDDI) is a high performance fiber optic dual token ring LAN with a data transmission rate of 100 Mbps over distances of up to 200 km. Up to 1000 nodes can be connected, and the maximum distance

between nodes is 2 km. It can be used in the same way as the 802 LANs to connect multiple hosts/IMPs, but another common use is as a backbone to connect copper LANs such as Ethernet. FDDI networks are now commonly being used, and the number of installations is predicted to grow. Already there is the possibility of extending the data transmission rate to 1 gigabits per second (Gbps) (Guy, 1992; Tanenbaum, 1989).

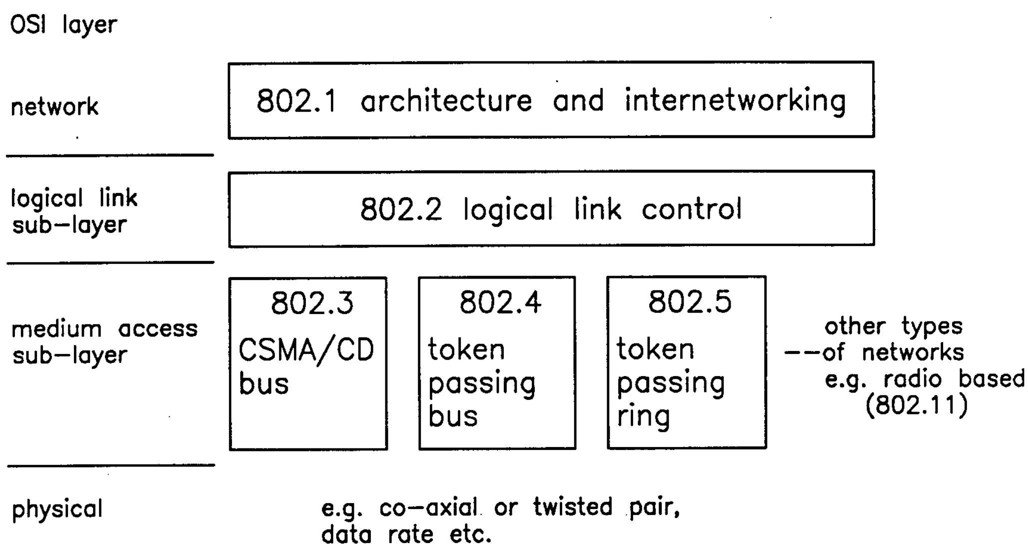

Figure 5-5. IEEE LAN standards.

A final note about LANs is that they can be interconnected or connected to WANs with a gateway. A gateway can be connection-oriented or connectionless and is used to connect two networks that use different protocols. Even a non-ISO-OSI network can be connected to an ISO-OSI network with a gateway because gateways have intelligence and act as a communications controller and protocol converter.

MANs

MANs have been partially defined by IEEE 802.6 Distributed Queue Dual Bus as a dual ring fiber optic network with a data transmission rate between 1.5 and 622 Mbps. MANs are designed to accommodate data, digital voice, and compressed video. While a MAN can be envisioned as a LAN covering a large metropolitan area, MANs are also expected to act as a gateway to WANs for existing Ethernet and token ring LANs. MANs are also expected to be compatible with the newer development of Broadband-Integrated Services Digital Network (B-ISDN) systems. B-ISDN is described below in the section covering WANs (Beauchamp, 1990; Guy, 1992; Vercelli, 1993).

WANs

One of the first major networks, ARPANET, was a WAN created by ARPA (now DARPA), the (Defense) Advanced Research Projects Agency of the

U.S. Department of Defense. In the late 1960s ARPA began stimulating research on computer networks by providing grants to many U.S. universities and a few private corporations. This research led to an experimental four node network that started in the late 1960s. It operated until 1990 and was a packet switched network using public leased lines operating at about 50 kilobits per second (kbps). Much of our present knowledge about networking came from the ARPANET project. In fact, the host-IMP terminology commonly used to describe computer networks came from ARPANET (Beauchamp, 1990; Tanenbaum, 1989).

Since many of the universities and government contractors connected to ARPANET also had their own LANs, these LANs were eventually connected to ARPANET leading to the ARPA internet (or simply called Internet). Internet is still functioning and is probably the most extensive WAN in existence today. Most of the below description of ARPANET's protocols also hold true for Internet (Tanenbaum, 1989; Krol, 1992).

ARPANET did not follow the ISO-OSI Reference Model at all. ARPANET actually predated the ISO-OSI model by more than ten years. The IMP-IMP protocol of ARPANET corresponded to a mixture of ISO-OSI layer 2 and 3 protocols. Another mechanism existed in ARPANET that explicitly verified the correct reception at the destination IMP of each packet sent by the source IMP. Strictly speaking, this mechanism was another layer of protocol, the source IMP to destination IMP protocol. However, this protocol does not exist in the ISO-OSI model. ARPANET did have protocols that corresponded fairly well to ISO-OSI layers 3 and 4. Corresponding to ISO-OSI layer 3 was ARPANET's IP (Internet Protocol) which was connectionless and designed to handle the interconnection of the vast number of WAN and LAN networks comprising Internet. Corresponding to ISO-OSI layer 4, ARPANET had a connection-oriented protocol called TCP (Transmission Control Protocol) which resembled the ISO-OSI layer 4 protocol in its general style, but differed in all the formats and details. TCP and IP are commonly used by other networks, giving rise to the popular TCP/IP description for a type of network. There were no layer 5 and 6 protocols in ARPANET. Various layer 7 protocols existed, but they were not structured the same way as their ISO-OSI counterparts. ARPANET was supported by the well-known protocols FTP (File Transfer Protocol), SMTP (Simple Mail Transfer Protocol), and TELNET (remote login). Various specialized protocols were available for other applications (Beauchamp, 1990; Tanenbaum, 1989).

The Integrated Services Digital Network (ISDN) is another important goal for WANs. The ISDN has been under development for a number of years, but only recently has it been available in anything other than trial form. Its purpose is to produce a pure digital WAN. Most WANs use the telephone companies' communication channels which historically began as analog networks. As communication technology advanced, the telephone companies replaced the communication channels between their main exchanges with digital technology, but the channels from the home or office to these exchanges remained analog. Therefore, to send a digital signal from one office to another, it first had to be modulated on an analog signal by a modem to travel from the originating office to one of the telephone companies exchanges. Then, the signal was digitized for transmission through the telephone companies' network of exchanges. Next, the signal was reconverted to an analog signal for transmission from the last exchange to the receiving office, and finally, the signal was demodulated by another modem to a digital signal that was supposedly the same as the originating digital signal. ISDN eliminates all of this analog to digital and digital to analog conversion by creating a pure digital network that would be compatible with the ISO-OSI Reference Model. The standards and necessary technologies for ISDN have been around for a number of years, but governments and large companies initially were not willing to invest the money necessary for its development and use. This hesitation is changing with the completion of large trials in various countries, and ISDN may gain widespread use in the next 5 to 10 years. However, Broadband-ISDN (B-ISDN) will probably also be available during this time, making wire based ISDN less attractive. B-ISDN incorporates fiber optics in the local loop from home or office to exchange allowing data rates up to 600 Mbps. Therefore, ISDN may become obsolete, and B-ISDN may be implemented in its place. Since B-ISDN would be a high data rate network, it is expected to be based around Asynchronous Transfer Mode (ATM) to reduce the time required to make routing decisions, which can be a major source of delay in data communications (Guy, 1992).

The U. S. government has a goal to develop and deploy a National Information Infrastructure (NII)

through the High Performance Computing and Communications (HPCC) Program. High performance computing refers to the full range of supercomputing activities including existing supercomputer systems, special purpose and experimental systems, and the new generation of large scale parallel architectures. HPCC intends to not only promote the advancement of high performance computers, but also to facilitate the progress of computer communications networks through NII. This infrastructure of "information superhighways" is to be a WAN with gigabit per second data transmission rates. It is proposed to revolutionize the way Americans work, learn, shop, and live; it will provide them the information they need, when they need it, and where they need it - whether in the form of text, images, sound, or video. The HPCC Program has already allowed users to improve the understanding of global warming, discover more effective and saver drugs, design safer and more fuel-efficient cars and aircraft, and access huge "digital libraries" of information. The HPCC Program has also accelerated the growth of Internet and enabled millions of users not only to exchange electronic mail, but to access computers, digital libraries, and research equipment around the world. The technology developed through HPCC, which allows Internet users to hold a video conference from their desks, is enabling researchers across the U. S. to collaborate as effectively as if they were in the same room (Committee on Physical, Mathematical, and Engineering Sciences, 1994).

Data Communications Media

The media used to transfer data from one computer to another can be put into three basic categories: storage media, physical wire media, and wireless media. Storage media include items that can hold data while disconnected from the source and destination computers. Physical wire media are materials which communicate data through a physical connection between computers. Wireless media transfer data through the air without a physical connection. All of these are used to carry bits of data or a bit stream from one computer to another.

<u>Storage Media</u>

Storage media refers to entities such as magnetic and optical disks and magnetic tape that can be used to carry the data from a source to a destination. The data is first copied onto the tape or disk from the source computer, and then the disk or tape is physically transported to the destination computer by foot, car, truck or any other form of transportation. Although not as sophisticated as other forms of communications media, storage media should be considered as a viable option when transporting large volumes of data a relatively short distance. For example, Tanenbaum notes that a truck carrying 200 magnetic tapes each holding 180 megabytes (MB) of data for an hour's drive between source and destination has an effective data rate of 288,000 megabits (Mb) in 3600 seconds or 80 Mbps. This not only shows the efficacy of storage media, but also demonstrates the magnitude of the problem of achieving a high data rate computer network (Tanenbaum, 1989).

<u>Physical Wire Media</u>

Physical wire media refers to materials which make a physical connection between two computers. They can be thought of as a type of wire and include the twisted pair, coaxial cable, and fiber optics.

Twisted Pair

For many applications a physical connection is needed to communicate data in the millisecond range rather than the minutes or hours required to move data via disk or tape. The simplest and most common physical connection is the twisted pair. This consists of two insulated copper wires twisted together. The most common example is the telephone system. Nearly all connections from the home or office to the telephone company are twisted pairs. The twisting reduces noise (a.k.a. interference or cross-talk), but noise still occurs as the twisted pairs are frequently bundled together from multiple nearby sources (e.g. an office building or apartment complex). In addition to noise, twisted pairs have two other disadvantages. They have a data rate limited to 10 Mbps with a few Mbps being typical, depending on the diameter of the wire and its length. Also, the signal is attenuated over long wires requiring amplification by repeaters every 2-3 km. Still, since they are inexpensive and can be used for digital communication, in addition to their traditional use for analog (voice) communication, they are used in local area networks (LANs) (Black, 1990; Tanenbaum, 1989).

Coaxial Cable

Coaxial cable consists of a solid inner copper wire core surrounded by an insulator which is encased by an outer braided conductor forming a cylinder around the inner conductor and finally covered with a plastic sheath for protection. The inner core carries the data on a single line while being shielded by the outer braided conductor which is grounded. This shielding greatly reduces the noise associated with twisted pairs. Also, the coaxial cable allows higher bandwidths and data rates as other advantages over the twisted pair. Therefore, the coaxial cable is popular in current LAN technology (Black, 1989; Tanenbaum, 1989).

There are two main types of coaxial cable used today. One is a 50-ohm (3/8 inch thick) cable which is used with a **baseband** signaling technique, and the other is a 75-ohm (1/2 inch thick) cable which is used with a **broadband** signaling technique. The names of these signaling techniques have been used to label the 50-ohm cable as baseband coaxial cable and the 75-ohm cable as broadband coaxial cable, but the inherent differences in the cables are less than the differences in how they are used. Baseband coaxial cable is used for digital communication and broadband coaxial cable is used for analog communication (Tanenbaum, 1989).

Baseband coaxial cable carries a single digital signal at speeds of up to 10 Mbps for a 1 km cable. Higher data rates are possible with shorter cable lengths, and the bandwidth varies with cable length (Tanenbaum, 1989).

Broadband coaxial cable uses standard cable television technology with a bandwidth of 300 MHz (or even 450 MHz) and can be as long as 100 km. To transmit digital signals along this analog transmission line, extra electronics are required to convert the signal from digital to analog prior to transmission and from analog to digital at the receiving computer. These electronics may use 1-4 Hz of bandwidth for each 1 bps of data transmission. Therefore, a 300 MHz cable can typically transmit 150 Mbps (Tanenbaum, 1989).

The main difference and advantage of broadband over baseband coaxial cable is that multiple signals can be sent along the same cable, just as cable TV transmits multiple channels along the same cable. This is done by segmenting the bandwidth to transmit a different signal in each segment or channel. In fact, one of the 6 MHz channels of TV broadcasting can be used to transmit a digital signal at 3 Mbps independent of the other channels. This segmentation is the way a broadband coaxial cable supports higher data rates than baseband (Tanenbaum, 1989).

Another key difference between broadband and baseband coaxial cable is that the analog signal carried by broadband cable periodically needs to be amplified and the amplifiers are unidirectional. Thus, the cable is transformed into a unidirectional channel. It is important to be able to send and receive data; therefore, it is important to be able to transmit data in both directions along the cable. This can be achieved by using two cables or by designating one range of channels for sending data and another range for receiving data. The latter requires another electronic device (called a headend) to change the range the message is carried within so that messages sent by one computer can be received by others (Tanenbaum, 1989).

Therefore, broadband coaxial cable requires extra electronic devices to be installed and tuned to accommodate the various frequency segments, but it can transmit with higher data rates for longer distances than baseband coaxial cable. Conversely, baseband is simple and easy to install, but lower data rates must be used for shorter distances. Consequently, broadband coaxial cable is most effective in large scale LANs transmitting voice, video, and data signals, while baseband coaxial cable tends to be used in short LANs transmitting data only (Tanenbaum, 1989).

Fiber Optics

Fiber optics have recently received much notoriety for their improvements to the previously described data communications media. A fiber optics cable is a glass or plastic fiber which carries or transmits light due to total internal reflection. It consists of a central glass or plastic core surrounded by a cylinder of glass or plastic cladding with a lower refractive index than the core. Both are encased by a protective cover. Due to the difference in the refractive index between the core and cladding, light traveling in the core within a certain angle is reflected back into the core (total internal reflection) (Beauchamp, 1990; Tanenbaum, 1989).

The light traveling in the fiber is produced by a light emitting diode (LED) or laser which converts an electrical signal from the sending computer to light. Typically, a bit of value 1 is transmitted by the presence of light and a bit of value 0 by the absence of light. At the receiving end of the fiber is a photodiode that converts the light into an electrical signal which can be interpreted by the receiving computer (Tanenbaum, 1989).

Fiber optic communication has many advantages over wire (twisted pair or coaxial cable) transmission. One of the biggest advantages is its capability for high transmission bandwidths. Visible light has a frequency of 10^8 MHz which would potentially translate to an enormous bandwidth. Currently, bandwidths can reach the gigahertz range depending on the length of the fiber, and data rates can reach 1 Gbps for 1 km. Even higher data rates have been achieved in the laboratory for shorter distances. Other advantages include low power loss along the fiber so that longer cable lengths can be achieved before a repeater is necessary, negligible cross-talk, no electrical interference, and no chance of sparking (not an electrically conducting medium) to cause an explosion or fire in a harsh environment. The fiber is also lightweight and thin with a diameter similar to the human hair (Tanenbaum, 1989).

Another key point is that an optical fiber is more difficult than coaxial cable to tap into or establish a new connection in an existing network. This is an advantage in terms of security but a disadvantage for network expansion (Tanenbaum, 1989).

The principle disadvantages to fiber optics are those of most new technologies. They are unfamiliar to network engineers and can be incompatible with present systems. Also, the interfaces required to convert an electrical signal to light and light to an electrical signal are more expensive than the electrical interfaces required for a copper wire network (Tanenbaum, 1989).

Therefore, fiber optics offers many advantages over copper wire. Most notably is its capacity for high data transmission rates. Since large data structures (images) are involved in 3-D anthropometry, a network with the high data rate that fiber optics offers may be desirable.

Wireless Media

Not all data transport needs to occur through a physical medium such as a floppy disk, a copper wire, or a glass fiber. Transmission can also occur through the air and is referred to as wireless media. The data can be carried by a radio wave, a microwave, a laser signal, or an infrared wave. All of these are forms of electro-magnetic radiation (which includes visible light) with different wavelengths or frequencies. Communication satellites are a special case of microwave transmission and will be discussed separately.

One of the advantages of wireless media over physical wire media is that a cable trench is not necessary. Digging a trench may seem trivial, but it can be time-consuming, expensive, and even illegal if the trench crosses a public road or a community neighborhood (Tanenbaum, 1989).

Radio and Microwave

Radio waves are generally considered to fall in the 30 kHz - 3 GHz range, while microwaves include the 3 - 30 GHz range. These are the carrier frequencies in which the data to be communicated can be modulated, which is a different concept than the bandwidth of transmission. Microwave and radio are both better suited for long transmissions but can be used for short transmissions as well. The distance traveled depends on the height of the antenna. A 100 m antenna can transmit a microwave almost 100 km. Microwaves are more commonly used with examples including long-distance telephone and television. Using a microwave carrier frequency of 8-10 GHz, a data rate of 100 Mbps can be achieved. The lower frequency radio waves can be used, but the data rate tends to be slow (Black, 1989; Guy, 1992; Tanenbaum, 1989).

Infrared and Laser

Infrared waves and laser signals occur at even higher frequencies or shorter wavelengths than radio or microwaves. Both laser and infrared are well suited for short communications. For example, two LANs in separate buildings can be connected using a laser or infrared transmitter and receiver on the roof of each building. This may be especially useful if the buildings are separated by a public road. Within each building, the LANs may be connected by copper wire or fiber optics. Laser and infrared are both fully digital and highly directional. They are both

susceptible to interference by weather conditions (especially rain and fog) depending on wavelength (Tanenbaum, 1989).

Communication Satellites

Communication satellites transmit data using microwaves. The data communication is accomplished when a ground station transmits a microwave signal carrying the data to a satellite. The satellite then amplifies the signal and transmits another microwave signal to a second ground station, and the second station receives the signal carrying the data.

The antennas of the ground stations can be simplified when the satellite is in geosynchronous orbit above the earth, as most communication satellites are today. A geosynchronous orbit occurs when the satellite is orbiting the earth with the same angular velocity as the earth is spinning; therefore, from the viewpoint of a ground station, the satellite is stationary in the sky, and the antenna does not need to be constantly steered to be in communication with the satellite. A satellite in geosynchronous orbit will be located 36,000 km above the equator (Black, 1989; Tanenbaum, 1989).

The data is again modulated upon the carrier microwave signal. The ideal carrier frequency for satellite communication is 1 -10 MHz because frequencies greater than 10 MHz can be attenuated by weather, especially rain. As these lower frequencies are becoming congested, higher frequencies are being used but require strategies to overcome the problem of attenuation by rain. The microwave signal sent from ground to satellite must be a different frequency than the signal sent from satellite to ground. These are called the uplink and downlink frequencies, respectively. If the uplink and downlink frequencies were not different, they would interfere with each other. The most common uplink/downlink frequency bands are the 4 GHz (3.7 - 4.2 GHz)/6 GHz (5.925 - 6.425 GHz) bands. As the 4/6 GHz bands are being overcrowded, the 12/14 GHz bands are beginning to be used. The 20/30 GHz bands have also been set aside for telecommunications (Beauchamp, 1990; Tanenbaum, 1989).

One disadvantage to satellite communication is the time delay between sending and receiving a data signal. Even though microwaves travel at the speed of light, a significant distance must be traveled. This causes a 240 - 300 millisecond delay which is long enough to be noticed with a telephone conversation and can cause problems in digital data transmission. For comparison, a transatlantic optical fiber has approximately a 20 millisecond delay, and typical coaxial cable has a transmission time of 5 microseconds for each km traveled (Beauchamp, 1990; Tanenbaum, 1989).

Another key point is that satellite communication is a broadcasting system. Many ground stations can send data to the same satellite, and many ground stations can receive data from the same satellite. This is similar to the way most LANs are structured and lends itself easily for network incorporation, but requires security measures to be taken. Therefore, the data communicated through a satellite may need to be encrypted. A side note to its broadcast nature is that the cost of a data transmission is independent of the distance between ground stations that are served by the same satellite (Beauchamp, 1990; Tanenbaum, 1989).

The performance characteristics include a bandwidth from 80 MHz for the early satellites to 2.3 GHz for the more recent satellites with a common bandwidth of 500 MHz. For a typical 4/6 GHz band transmission with a 500 MHz bandwidth for both the uplink and downlink frequencies, the bandwidth is usually split into 12 channels each with a 36 MHz bandwidth. Each of these channels is capable of a data rate of 50 Mbps (Beauchamp, 1990; Tanenbaum, 1989).

Data Formats

Data in raw form consists of binary digits which represent a physical or mathematical entity (e.g., an image). The way these bits of data are organized is referred to as the format of the data. For a computer to be able to extract the physical or mathematical entity from the raw data, it is critical for the computer to know the format of the data and be able to read data of that particular format. Therefore, numerous standard data formats have been devised to describe many types of data from multiple disciplines. Software is then required to allow a computer to interpret or read the data. Some data formats are proprietary, resulting in limited availability of information characterizing these formats. Other data formats are public and intended to facilitate exchange of data between equipment manufactured by multiple vendors. There are even data formats which can be called self-describing

because the data file itself describes the format of the data it contains. A computer can read a self-describing data file and extract the data it contains without knowing anything about the data file beforehand.

A Spyglass document (Fortner, 1992) summarizes some of the data formats available today. Due to the conciseness of this document and the relative paucity of information elsewhere in the literature, parts of the document are reproduced below with minor modifications.

BUFR is a machine-independent data format standard for the World Meteorological Organization used for self-defining meteorological and oceanographic data. BUFR provides several decoders to convert integers and floating point data from an internal format to native formats. BUFR emphasizes the physical data file format. The format is considered more machine-independent than netCDF.

CDF (Common Data Format) is a widely used data format standard developed by NASA for storing multi-dimensional gridded scientific data with user defined annotations. CDF is used in many disciplines and is supported by a wide variety of analysis and display applications. CDF uses a column format to store the following number types: ASCII text, 16-bit and 32-bit integers, and 32-bit and 64-bit floating point numbers. A single dataset may be stored in separate files, which makes it easy to add data to an existing dataset. CDF stores the data in XDR (external data representation) format, which is a nonproprietary standard for storing data to be machine-independent. XDR was originally developed by Sun Microsystems. XDR uses the IEEE standard for floating point numbers, and has been implemented for Suns, Vaxes, Macintoshes, IBMs, Crays, and other computers. CDF is primarily a subroutine-library-based format. Because of this emphasis the subroutines are relatively simple to use. The dynamic addition of data to an existing CDF file is also a popular feature. In CDF the XDR implementation is machine-dependent, limiting the portability of the data files. The ability to annotate dimensions in CDF is weak.

CGM (Computer Graphics Metafile) is widely used for computer graphics. Data for bit-mapped images and for vector objects, such as lines, circles, and polygons can be stored in CGM files. A CGM metafile can be used to store and organize several images in the same file. Individual images in the metafile can be accessed randomly. CGM metafiles support the following number types: 8-bit, 16-bit, 24-bit, and 32-bit integer, 32-bit and 64-bit floating point, and ASCII text data. CGM files are considered fairly machine-independent. CGM allows the incorporation of nongraphical and nonstandardized information into the data files. Some people consider this extensibility a weakness, since some features added by a programmer may be unreadable by a CGM interpreter.

DICOM (Digital Imaging and Communications in Medicine) is being developed by the American College of Radiology (ACR) and the National Electrical Manufacturers Association (NEMA) for the storage of medical image data. The standard is also known as ACR-NEMA, after the two sponsoring organizations. DICOM image data is stored as a 2D matrix of unsigned or signed integers. Typically, the integers are 16-bits, although other bit depths are supported. The header for a DICOM file is a variable length record which describes the data. Support for 3-D matrix data is being considered for the future.

DLIS (Digital Log Interchange Standard), also known as RP66 (Recommended Practice 66), is a data format standard created by the American Petroleum Institute (API) for geophysical data. It is used to store multi-dimensional arrays of various data types including floating point numbers, integers, and complex numbers. DLIS is a self-describing data format which supports the use of annotations such as name, units, etc.

DXF (Data Exchange Format) is widely used in CAD (Computer Aided Design) applications to store polygonal data. Each data element in DXF consists of two lines. The first line consists of a 'type' code (indicating whether the data element is an x-coordinate, a y-coordinate, etc.). The second line is the actual data (32-bit integer or floating point). DXF was created for AutoCAD and was designed specifically for internal use by the company. However, the standard has since been adapted by many application software companies.

EPS (Encapsulated PostScript) is a proprietary graphics format developed by Adobe Systems, Inc. primarily for use in printers. It is actually a computer language for describing pages that consist of text, graphics, and raster images. When printing to a

Postscript printer, your computer actually creates a Postscript computer program, and sends it to the computer inside the printer, which executes the program. Postscript is primarily an ASCII standard, and is not designed for storing numerical data. The EPS (also known as EPSF) is a file format for storing single page illustrations. The format uses a subset of the Postscript commands. Full Postscript files typically describe many pages graphically in the same file. Most EPS files contain information on the size of the resulting illustration, a title, a list of fonts used by the illustration, and a machine-dependent preview version of the illustration (such as a PICT for Macintosh EPS files). This preview is used for on-screen display only, and is thrown away when printing.

Erdas is the standard format used by Erdas image processing software for remote sensing data usually from the global information satellites. The 2D matrix image data is stored as 4-bit, 8-bit, or 16-bit integers. Other analysis software packages, such as MultiSpec developed at Purdue University, use Erdas as their native format.

FITS (Flexible Image Transport System) is used primarily by astronomers. It can store arrays of data with dimensions ranging from 1 to 999. The data types supported by FITS are: character, unsigned 8-bit integer, two's complement signed 16-bit and 32-bit integer, and IEEE single-precision and double-precision floating point numbers. FITS supports storing column data as ASCII text. Recently the FITS standard has been extended to storing binary column data (FITS BINTABLE format). The original FITS standard was published in 1981. FITS is the standard format for most major radio and optical astronomical observatories. It has been endorsed by NASA's Science Data Systems Standards Office and the International Astronomy Union. FITS was originally designed to store images in a machine-independent format. It has since been extended to store numerical data. A FITS file contains a header and then the data. The header and the data may be stored in the same file or in separate files. The header is ASCII text, whereas the data is usually binary.

Flux is an internal general data format for apE (animation production Environment), a visualization system developed at the Ohio Supercomputer Center.

GRIB was developed by the World Meteorological Organization for meteorological and oceanographic data. GRIB stores packed binary integer data in multi-dimensional arrays or in irregular grids.

HDF (Hierarchical Data Format) is a scientific data file format developed at the National Center for Superconducting Applications (NCSA) at the University of Illinois at Urbana-Champaign. It is a machine-independent binary file format standard for storing matrix, column, and polygonal data from a wide variety of disciplines.

IGES (Initial Graphics Exchange Specification) is a general format for transporting and storing polygonal data for CAD systems. It supports a more general set of geometry types than DXF and is designed to be system-independent.

netCDF is an extension of CDF developed by the National Center for Atmospheric Research (NCAR) and Unidata. netCDF stores multi-dimensional gridded data in a self-describing fashion and supports ASCII text, 16-bit and 32-bit integers, and 32-bit and 64-bit floating point numbers. Each netCDF dataset contains information on dimensions, variables, and attributes. The dimension has both name and size and is used by all of the variables in the dataset. netCDF uses XDR for bytes, integers, and floating point numbers (see XDR write-up in CDR section above).

PDS (Planetary Data System) was developed by NASA's Jet Propulsion Lab (JPL) to handle the data coming from various planetary exploration missions. PDS generally stores image data in 2D matrix form as 8-bit unsigned integers. PDS also supports column data, spectral data, and 3-D matrix data. A PDS data file includes an ASCII text header describing the data; the header may be attached to or separate from the data. PDS is machine-independent and is intended to be a flexible formatting standard. The standard has evolved such that many implementations are now incompatible.

PHIGS (Programmer's Hierarchical Interactive Graphics Standard) is a graphics standard that allows the user to specify geometrical objects and then refer to multiple copies of the object. An extension to this standard that allows shading and more complex geometries is called PHIGS+.

PICT is the primary graphics standard for Macintosh computers. PICT can store image data as 1-bit, 2-bit, 4-bit, 8-bit, 16-bit, and 32-bit unsigned integers. Besides images, PICT files contain information on lines and characters. Because the use of PICT files is so widespread, many programs on computers other than the Macintosh will read or write PICT files.

Plot3-D is a visualization program which was developed at NASA Ames for use in computational fluid dynamics. It uses an internal data format of 3-D matrix of binary data with either a uniform or a warped grid. Every dataset consists of two files: one with the grid description, and another with the data. The Plot3-D file format is very specific for 3-D computational fluid dynamics, which is both a strength and a weakness.

SEG-Y was created by the Society of Exploration Geophysicists (SEG) for seismic data. The data is stored in multi-dimensional arrays of IBM-format floating point numbers. SEG-Y also supports 2-bit and 4-bit integer data although they are rarely used.

TIFF (Tagged Image File Format) was developed by Microsoft and Aldus primarily to store images in a machine-independent way. Number types supported include: 8-bit unsigned integers, ASCII codes, 16-bit and 32-bit unsigned integers, and two 32-bit unsigned integers, where the first represents the numerator of a fraction and the second represents the denominator. TIFF data is stored one image at a time in a tagged data block. TIFF then defines a linked list of tag blocks. TIFF is one of the most commonly used standardized data formats, especially for the storage of image (2D matrix) data.

DICOM, introduced above, warrants further description as many of the manufacturers of radiologic imaging devices (computed tomography (CT), magnetic resonance (MR), ultrasound, nuclear medicine, and computed radiography (CR)) have developed software to implement the DICOM standard. In fact, 20 manufacturers recently demonstrated the ability of DICOM to transparently transfer data between different vendors at the Radiological Society of North America (RSNA) annual meeting in Chicago, IL during November and December 1993. The importance of DICOM to the proposed 3-D surface anthropometry standardization is that DICOM has been successfully shown to be able to allow transfer of some of the types of images proposed to be collected (CT, MR, etc.). It is not clear whether DICOM can be effectively used to transfer 3-D surface scan images. To help expedite the implementation of DICOM, it is the intent of NEMA and other groups developing the standard to make the software available early in 1994. The document describing DICOM is available from NEMA.

Since 1983, ACR and NEMA have been engaged in developing standards related to medical imaging. This alliance of users and manufacturers was formed to meet the needs of the medical imaging community as its use of digital imaging technology increased. The development of electronic PACS, which could connect a number of medical imaging devices together in a network, led to the need for a standard interface and data structure for use on imaging equipment. Since medical image files tend to be very large and include much text information along with the image, the need for a fast, flexible, and extensible standard was quickly established. The ACR-NEMA Digital Imaging and Communications Standards Committee developed a standard which met these needs. The standard (ACR-NEMA 300-1988) was first published in 1985 and revised in 1988. It is increasingly available from equipment manufacturers. The current work of the ACR-NEMA Committee has been to extend the standard to incorporate direct network connection features, and build on standards work done by ISO in its OSI series. This new standard, DICOM, follows an object-oriented design methodology and makes use of as many existing internationally accepted standards as possible. Horii (1992) gives a brief overview of the requirements for communications standards in medical imaging, a history of the ACR-NEMA effort and what it has produced, and a description of the DICOM standard. Bidgood and Horii (1992) have written a similar overview of DICOM.

CURRENT PACS REVIEW

This section on picture archiving and communications systems (PACS) is included because these systems may become the standard means of transferring patient data (images and text) within the hospital environment. This seems appropriate since this working group is interested in collecting human data, some of which will be of the same format (e. g., CT, MR, etc.) as patient data. One way in which this group's requirements will differ from those of PACS

is that a PACS is designed with the majority of its users to be located in the same general vicinity. Therefore, PACS tend to be based upon a LAN within a hospital or to connect a few hospitals each having their own LAN. Teleradiology, transferring medical images over telephone lines, can be a component of a PACS and gives these systems the ability to transfer data longer distances. Although, teleradiology is not the dominant design focus for PACS, this working group's proposal will involve transferring anthropometric image and text data to multiple users throughout the international community. Consequently, WAN technology using the telephone system may be required. Therefore, a review of the current technology for PACS and teleradiology will be given by summarizing or reproducing the abstracts of selected papers with minor modifications. Furthermore, since the user of the proposed 3-D surface anthropometry database and communication system will interact with the system by using a computer workstation, the reader should refer to Vannier's review of the 3-D Anthropometry Workstation in the Visualization, Modeling and Analysis chapter.

PACS: Picture Archiving and Communication System Developments Expected in the 1990s

Drew, Lorah, Lydon, and Novak (1992) discuss a historical view of PACS noting that compared with the expectations for PACS ten years ago, progress has been slow, but by recognizing that teleradiology, digital archives, and CR can be regarded as PAC subsystems, and that systems confined to a single modality can be regarded as mini-PACS, they stress that remarkable progress has been made. In addition, a calculation of the requirements for PACS in a typical 500-bed hospital is given as 12.5 terabytes to store all images acquired over a 5 year period and an 89 Mbps data transmission rate for acceptable access to the images. They assert that "despite the fact that satisfactory networks and archives are available or potentially available for a filmless PACS, no such systems exist. We believe that the reason is that satisfactory workstations for radiologists do not exist." Finally, a discussion of the future of PACS is given concluding "that full-scale PACS are unlikely to materialize in this decade, except in special cases like the military services and the Veterans Administration (VA), where the same economic considerations that govern usual medical practice do not apply."

Therefore, the next series of articles will summarize the PACS being implemented in U.S. military medical centers and the VA today.

Design Strategy and Implementation of the Medical Diagnostic Image Support System at Two Large Military Medical Centers

Smith, Smith, Sauls, Cawthon, and Telepak (1992) discuss the implementation of the Medical Diagnostic Imaging Support (MDIS) system at Madigen Army Medical Center (MAMC), Tacoma, Washington, and Brooke Army Medical Center (BAMC), San Antonio, Texas. The MDIS system contract for federal medical treatment facilities was awarded to Loral/Siemens in the Fall of 1991. This contract places "filmless" imaging in a variety of situations from small clinics to large medical centers. The MDIS system approach is a "turn-key", performance based specification driven by clinical requirements. The installation at MAMC is an example of installation for a new 416-bed hospital with a large outpatient clinic which opened March, 1992. On the other hand, BAMC represents an installation of a PACS at an existing facility. Specifically, they discuss personnel infrastructure, configuration planning, installation planning, and training issues for a full PACS implementation.

Rationale for a Large Facility PACS Implementation

Donnelly, Hindel, and Anderson (1992) discuss the implementation of MDIS at Wright-Patterson USAF Medical Center (WPMC). They present an operational overview of WPMC, a description of the deficiencies in WPMC's current image management system, and a discussion of the PACS installed in the summer of 1992.

Architecture of a High Performance PACS Based on a Shared File System

Glicksman, Wilson, Perry, and Prior (1992) discuss the architecture of MDIS. MDIS utilizes an advanced, high speed, fault tolerant image file server or Working Storage Unit (WSU) combined with 100 Mbps fiber optic data links. This central shared file server is capable of supporting the needs of more than 100 workstations and acquisition devices at interactive rates. If additional performance is required, additional working storage units may be configured in a hyper-star topology. Specialized processing and display hardware is used to enhance Apple Macintosh personal computers to provide a

family of low cost, easy to use, yet extremely powerful medical image workstations. The Siemens Litebox" application software provides a consistent look and feel to the user interface of all workstations in the family. Modern database and wide area communications technologies combine to support not only large hospital PACS but also outlying clinics and smaller facilities. Basic Radiologic Information System (RIS) functionality is integrated into the PACS database for convenience and data integrity.

Modeling and Simulation of a High Performance PACS Based on a Shared File System Architecture

Meredith, Anderson, Wirsz, Prior, and Wilson (1992) model the MDIS system to assess system performance. The system is modeled as a heterogeneous network of processing elements, transfer devices and storage units. They discuss the System Model, focusing on the flow of image traffic throughout the system, and the Workstation Model, focusing on the internal processing in the different types of workstations. Specifically, they describe some of the issues addressed with the models, the modeling techniques used, and the performance results from the simulations. Important parameters of interest include the following: time to retrieve images form different possible storage locations and the utilization levels of the transfer devices and other key hardware components. To understand system performance under fully loaded conditions, they model in detail the MAMC. For the complete retrieval of the first image of an exam from short term storage (the WSU), from sending the read command to finishing the painting of the image on the screen, the MDIS requirement is 5 seconds. For the MAMC simulation, they obtained mean response times of 0.748 and 1.401 seconds, for optimized and standardized workstations, respectively. The probability of exceeding the 5 second limit was less than 0.05% for the optimized workstation and about 0.2% for the standardized workstations.

Utilization of an Integrated Multidepartmental Medical Imaging System in a Hospital Environment

Dayhoff and Maloney (1992) measure the utilization of the VA's Decentralized Hospital Computer Program (DHCP) for design and feedback during the development process. As part of this paper, they describe DHCP, which is a distributed imaging system that provides image management and communications functionality as an integral part of the VA's integrated hospital information system. DHCP incorporates images, not only radiologic images like PACS, but also images from cardiology studies, microscopic pathology slides, in situ pathology as seen in the operating room, dermatologic and ophthalmologic lesions, and endoscopic examinations. The system's network provides connectivity for multiple image servers, 80386-based high resolution true color image workstations, and the networked DHCP hospital information system. It also provides shared services, such as image printing, image processing, file transfer and format conversion, image archiving to optical disk jukebox, and backup. The initial test site for the DHCP Integrated Imaging System is the Washington DC VA Medical Center, a 700-bed facility that provides acute and long-term care for veterans of the Washington area.

Digital Archive Center: Implementation for a Radiology Department

Wong, Taira, and Huang (1992) describe the implementation of a digital archive center for a radiology department in a 700-bed teaching hospital. The archive center consists of two identical archive systems, each comprising five components: an archive server, a data-base server, an optical disk library, a stand-alone optical disk drive, and a communication network. The network is a combination of 10 Mbps Ethernet, 100 Mbps FDDI, and 1 Gbps UltraNet networks. An image management system controls the image traffic from acquisition devices to display stations. A fault-tolerant mechanism was built into the archive center to achieve a 100% uptime. The system archives all digital images from three MR units and four CT scanners and selected images from three CR systems and two laser film digitizers, resulting in 1.5 to 2.0 gigabytes of images to be archived each workday.

European Activities Towards a Hospital-Integrated PACS Based on Open Systems

Kouwenberg, Ottes, and Bakker (1991) describe the PACS research activity in Europe as of February 1991. The activities all work in the direction of an Open Systems architecture. The Research and Development in Advanced Communication Technologies project in teleradiology (RACE/TELEMED) is funded by the European Community (EC) to investigate the use of high speed networks within teleradiology. It is proposed to be based on the European-wide broadband ISDN network (up to 140 Mbps) which is expected to be in

place in 1995. Advanced Informatics in Medicine (AIM) had an exploratory phase in which it funded 42 consortia with EC money. Two of these consortia are described in Kouwenberg's paper, 'Foundations for a Hospital Integrated PACS (HIPACS) and 'Image Management Archiving and Communication System (PACS-IMACS). The AIM/HIPACS project was broken down into 6 main tasks: 1) the generic integration of PACS with HIS and RIS, 2) implementation and evaluation of a prototype of a high-speed network for image transfer, 3) development of a model of a heterogeneous network structure to be used to study routing optimization of image and other data in existing and future networks, 4) multi-media data-base concept with facilities for intelligent information retrieval, 5) design of an adaptive user-interface for increased diagnostic efficiency of existing image workstations, and 6) the development of methodologies for indexing of images on their contents. The AIM/PACS-IMACS project performed an evaluation of the clinical usage of PACS at various hospitals in Europe (mainly in Italy). Other European-wide PACS related projects are also summarized including the ESPRIT RICHE (Health Care Information and Communication Network for Europe) project, the ISCAMI (Integrated Systems for Computer-Assisted Management and Manipulation of Medical Images) activity, EuroPACS/ECR-SCDI (European Committee for Recommendation - Standards in Computer aspects of Diagnostic Imaging), and a project proposal for HIPACS-2.

Hospital Integrated Picture Archiving and Communication System (HIPACS) at the University Hospital of Geneva

Ratib, Ligier, Hochstrasser, and Scherrer (1991) discuss the PACS under development at the University Hospital of Geneva which is a hospital-wide Image Management System for radiological as well as non-radiological medical images and is a part of one of the widest hospital information systems (HIS) in Switzerland (Diogene System). It is based on a multi-vendor open architecture and a set of widely available industry standards: Unix as the operating system, TCP-IP as network protocol, and an SQL-based distributed database (INGRES) that handles both the PACS and the HIS. The PACS is based on a distributed architecture of servers of two types: the Archive Servers connected to the sources of images and equipped with large optical disk libraries (Juke Boxes) and Display Servers distributed over the hospital. A standard image storage format was developed based on the ACR-NEMA standard. This file format, PAPYRUS, allows storage of sets of images as a sequence of ACR-NEMA messages in an "encapsulated" file structure. The first version of the PAPYRUS format has been extensively modified after its evaluation by a technical working group of TELEMED. PAPYRUS was adopted as a standard file format for image communication for TELEMED. In order to provide a more uniform user interface on a variety of different workstations, a common platform for image display and manipulation named OSIRIS was developed based on the X-11 windowing system and OSF/Motif extension. Such a platform is designed to be portable to any computer running Unix and equipped with a graphic display system running X-11. Furthermore, because this software is written in the object oriented language C++, it is easily expandable and easily adaptable to different needs and requirements.

An Integrated Picture Archiving and Communications System-Radiology Information System in a Radiological Department

Wiltgen, Gell, Graif, Stubler, Kainz, and Pitzler (1993) present an integrated PACS-RIS which runs as part of the daily routine in the Department of Radiology at the University of Graz. Although the PACS and RIS have been developed independently, the two systems are interfaced to ensure a unified and consistent long-term archive. The configuration connects four CT scanners (one of them situated at a distance of 1 km), an MR scanner, a digital subtraction angiography unit, an evaluation console, a diagnostic console, an image display console, an archive with two optical disk drives, and several RIS terminals. The configuration allows the routine archiving of all examinations on optical disks independent of reporting. The management of the optical disks is performed by the RIS. Images can be selected for retrieval via the RIS by using patient identification or medical criteria. A special software process (PACS-MONITOR) enables the user to survey and manage image communication, archiving, and retrieval as well as to get information about the status of the system at any time and handle the different procedures in the PACS. The system is active 24 hours a day. To make the PACS operation as independent as possible form the permanent presence of a system manager (electronic data processing expert), a rule-based expert system (OPERAS; OPERating ASsistant) is in use to localize and eliminate malfunctions that occur

during routine work. The PACS-RIS reduces labor and speeds access to images within radiology and clinical departments.

The following seven papers give a more technical discussion of PACS.

Subsystem Throughputs of a Clinical Picture Archiving and Communications System

Wong and Huang (1992) measured the throughput rates of individual PACS subsystems including the acquisition, archive, display, and communication network as a basis of evaluating the overall throughput of their clinical PACS. The throughput rate of each PACS subsystem was measured in terms of average residence time of individual images in the subsystem. The residence time of a image in a PACS subsystem was determined by the total time the image was required to be processed within the subsystem. The overall throughput of the PACS was measured as the total residence time of an image in the various subsystems. They also measured throughputs of the PACS subsystems using three types of networks (Ethernet; FDDI; and UltraNet, UltraNetwork Technologies, San Jose, CA), and the results were compared. Approximately 200 gigabytes of data transactions including MR, CT and CR images from their PACS were analyzed. Results show that PACS throughput was limited by three factors: (1) low-speed data interface used in the radiologic imaging devices and archive devices; (2) competition for systems processing time among the PACS processes; and (3) network degradation caused by heavy network traffic. They concluded that PACS performance could be improved with a well-designed network architecture, a job prioritizing mechanism, and an image routing strategy. However, device-dependent low-speed data interface has limited PACS performance.

Network Data Rate Requirement Analysis for PACS

Toshimitsu et al. (1990) develop a simulation model to analyze the network data rate requirement for a PACS in a medium sized (400-bed) hospital using a circuit switching network. The system modeled consisted of one database system, 20 radiology modalities (i.e. film digitizers, CT, MR, etc.), and 29 workstations. The data load is based on data from an existing hospital, and conventional X-ray and fluoroscopy images are 2048x2048x8bits while the images from digital modalities (CT, MR, etc.) are 512x512x16bits. They perform the simulation with and without preloading the system to load the radiologist's workstation with the next study while he/she is reading the current study. Their conclusions, without image compression, are: (1) a network with a data rate of 100 Mbps can transfer typical radiology studies in 3 seconds; and (2) when preloading is used, a 20 Mbps data transmission network is sufficient. They point out that these calculations are made using assumptions that do not apply to a real PACS; therefore, the necessary data rates would be higher to achieve the transmission times suggested, or using the data rates given, a longer transmission time would result.

Multiple Communication Networks for a Radiological PACS

Wong, Stewart, Lou, Chan, and Huang (1991) have implemented a communication network connecting multiple buildings for their PACS in the Radiology Department at UCLA. The network consists of three types of LANs an a 1.0-km fiber optic link connecting the outpatient and inpatient facilities. Images from radiologic imaging devices (4 CT scanners, 5 MR scanners, 4 CR units, and 5 film digitizers) are transmitted to the acquisition computers via the Ethernet LAN. The FDDI LAN then provides data communication among the cluster controllers, the acquisition computers, and the data base servers. A 1 Gbps UltraNet LAN is used to route images from the cluster controllers to remote display workstations. All inter-building connections are through fiber optic cables. Among these multiple networks, Ethernet offers multi-access to the multimodal PACS in image acquisition, FDDI controls a fast data flow so that all acquired images have a shorter residence time on local disks, and UltraNet provides high-speed transfer of images form the cluster controllers to the display workstations. The three-tiered functionality of Ethernet, FDDI, and UltraNet eliminates network traffic bottlenecks and hence provides high performance in image communication. The delay time of a 2K x 2K x 8-bit CR image (4 MBytes) form acquisition to display is less than 5 minutes. In addition, the standard Ethernet serves as a backup to guarantee network connectivity of the entire PACS. A clinical release of the multimodal PACS that utilizes this three-tiered network architecture was expected in March 1991.

Optimization of image transfer from the Central Archive to Workstations in a PACS

D'Lugin, Boehme, Choplin, Maynard, and Wolfman (1990) note that despite the much-discussed advantages of the all-digital radiology department, the speed of electronic display continues to be a major obstacle to its acceptance. Physicians generally agree that sophisticated workstation functionality cannot compensate for an interpretation environment that delays diagnosis. Two design schemes have been devised and discussed at length at the Bowman Gray School of Medicine (BGSM) that will improve the efficiency of image transmission significantly. BGSM is working with AT&T and Philips Medical Systems as a co-development site for CommView", a distributed PACS. The first of these schemes is image routing and pre-loading. The central archive can use information associated with each exam and a set of rules to predict which workstations will be used to read the exam. The images can therefore be sent automatically before the physician arrives at the workstation to interpret a series of exams. The second scheme, which is intimately associated with the first, allows a workstation to manage its own local disk to remove copies of exams so that new ones may be pre-loaded. This disk management algorithm assigns priorities to the exams based on their status in the acquisition/interpretation cycle and performs automatic deletion as the workstation's disk reaches its capacity. The effect is a virtually limitless disk that eliminates the time-consuming task of manual deletion and retrieval of images.

A Demonstration of Medical Communications Based on an ATM Broadband Network Technology

Cox et al. (1992) describe a demonstration project at Washington University in collaboration with Southwestern Bell and NEC-America that provides a testbed for deployment of ATM broadband network technology supporting both LAN and WAN experiments in multimedia medical communications. A network based on four geographically dispersed ATM switches supports rapid display of high-resolution medical images, patient information, digital video, and digitized real-time physiological signals at channel rates of 100 Mbps. A prototype configuration of an Inquiry & Display station is based on the NeXT computer with auxiliary displays for the medical images. The typical performance for the delivery of a 1024 x 1024 image is under 2 seconds, while a 2048 x 2048 image requires about 4 seconds. The initial demonstration included a patient undergoing an exercise electrocardiogram at one site and a primary care physician at another site observing the patient via video while consulting with a cardiologist at another site also via video.

ISDN: Early Experiments as a Wide-Area Extension to LAN-based PACS

Blaine, Ferguson, Studt, and Whitman (1990) describe an ISDN test configuration, developed in collaboration with SBC Technology Resources Inc., which has been utilized to gain experience with both hardware and software interface issues relevant to wide-area extensions of PACS. Example workstations capable of inquiry and display of radiological information have been interfaced to the ISDN network and tested. A DECnet router was used to interface their Ethernet-based PACS to an ISDN network. Average throughput rates of approximately 60 Kbps for the 1B (64 Kbps) channel and 120 Kbps for the 2B (128 Kbps) channel were measured. This translated to calculated transmission times of 6.5 seconds for MR images (256 x 256 x 2 bytes/pixel) and 87 seconds for CR images (1024 x 1024 x 2 bytes/pixel).

Initial observations of ISDN connect and disconnect times were less than 1 second for the embedded and between 2 and 6 seconds for the external ISDN terminal adapters. They also note that B-ISDN offerings of 150 Mbps and 600 Mbps promise sub-second wide-area image delivery times which match or exceed those of anticipated LAN technology.

Medical Applications in a B-ISDN Field Trial

Chipman et al. (1992) discuss a B-ISDN field trial network that has been deployed in North Carolina as a multiservice testbed for advanced applications research and development. They describe two medical applications of this field trial network. Dynamic radiation therapy planning is the application being investigated in VISTAnet. This application requires communications rates approaching 1 Gbps to support communications among a supercomputer, two massively parallel image processors, and a medical workstation. The industry-standard 32-bit high performance parallel interface (HIPPI) was chosen as the customer interface for this application and is connected to a 622 Mbps B-ISDN user-network interface (UNI). Remote consulting is the application being investigated in the Medical Information Communications Application (MICA). The industry-

standard 32-bit VME interface, which is widely used on high-end workstations and computers, was chosen to support the image display workstation requirements as is connected to a 155 Mbps B-ISDN UNI. The VISTAnet and MICA field trials are intended to address high-performance applications which require network capabilities that will not become available commercially until the 1993-1994 time frame.

Teleradiology - A Practical System for Teleimaging

Teleimaging, the remote transmission, display and analysis of image data sets, is practical and important since users are widely distributed geographically, and many have access to digital computer networks. Borrowing from experience in medical radiology, the transmission of image data sets over existing and future telecommunications systems has been developed.

Teleradiology: An Assessment

Batnitzky et al. (1990) discuss that a teleradiology system acquires radiographic images at one location and transmits them to one or more remote sites, where they are displayed and/or converted to hard copy. These systems often employ WANs. Their goal is to provide improved radiologic service at all sites on the network. Experience in the use of teleradiology systems has demonstrated the need for a laser film digitizer, an optical disk, and a high-quality display and/or laser film printer at each site. The laser film digitizer scans a radiographic film to create a digital image which can be sent over the WAN from one site to another. The display and/or film printer is used to convert the digital image coming across the WAN into a visible format (softcopy and/or hardcopy, respectively).

High-Resolution Digital Teleradiology: A Perspective

Kuduvalli, Rangayyan, and Desautels (1991) discuss that teleradiology has come a long way from analog transmission systems using slow-scan television over standard telephone lines, to present-day, commercially available, microcomputer-based, low-resolution teleradiology systems. Some of the commercially available digital teleradiology systems are approaching the resolution requirements of high-resolution teleradiology as a feasible alternative to transportation of films/patients from remote areas to centers with better diagnostic facilities. The availability of high-resolution digitizers, display units, and digital hard copiers has made high-resolution digital teleradiology a feasible concept. Although the use of satellite channels can speed up the transmission of radiographic image data, with widespread acceptance of high-resolution teleradiology systems in the foreseeable future, the sheer amount of data involved in this field will give rise to problems of data transmission and storage. Data compression can bring down the amount of data involved in the transmission and storage of images generated at the remote sites and have a significant impact on the economics of the next generation of teleradiology systems. Commercially available systems have addressed the problem of transmission of data, but appear to have grossly ignored the potential of data compression techniques, optimized for medical images, to affect the economics of future teleradiology systems. Kuduvalli et al. have developed a number of compression techniques for reversible compression of medical images. Their experiments with these compression techniques have shown that compression of the order of 4:1 is possible for a class of high-resolution medical images. Use of pattern recognition techniques offers a significant potential to improve compression even further. They plan to use these techniques in the prototype teleradiology system being developed at The University of Calgary.

WAN Strategies for Teleradiology Systems

Dwyer, Stewart, and Sayre (1992) discuss that teleradiology systems require the use of WANs. The design and implementation of a WAN depends on the number of images to be transmitted, the desired digital image throughput, based on signaling rate, and the cost of the communications link. Image transmission load must be estimated before the communications link can be selected. Communications links used in WANs include T-1 carrier (1.544 Mbps) point-to-point service, digital service (DS)-1 (1.544 Mbps) dial-up service, DS-3 (44.736 Mbps) point-to-point service, DS-0 (56 Kbps) dial-up service, digital microwave, fiber optic local loop carriers, and IEEE 802.6 standard MANs. Depending on the distance between sites, T-1 service may be less costly than DS-1 service; however, for distances more than 200 miles, DS-1 service can be less expensive and more flexible. Both of these services and DS-0 service have lower signaling rates than DS-3, which is the fastest and most expensive

link. Microwave and fiber optic links are less expensive, but have distance limitations of 14 and 30 miles, respectively. MANs are still being developed but hold the promise of higher signaling rates at lower costs.

Teleradiology with ISDN and JPEG compression

Blaine et al. (1992) discuss that the importance of remote access to both radiological images and medical information has stimulated many demonstration projects that use a variety of telecommunications providers' offerings. Teleradiology, through modest cost channels, can achieve adequate response times using a combination of narrow-band integrated services digital network (N-ISDN) and data compression. A demonstration project, developed at the Mallickrodt Institute of Radiology and Southwestern Bell Technology Resources, Inc., uses the aggregate bandwidth of two B channels (achieving a rate of 120 kbps) and a block-oriented discrete cosine transform compression/decompression implementation based on the Joint Photographic Experts Group (JPEG) Standard for Still Image Compression. System response measurements for an Inquiry and Display Station accessing the Mallickrodt Institute of Radiology's Radiology Image and Information Management Testbed via the N-ISDN connection show times to be within 20 seconds. Viewing applications have been shown at sites within St. Louis and at Radiological Society of North America national meetings from 1990 through 1993.

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CHAPTER VI: USER INTERFACE

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INTRODUCTION

The user interface is the visual and interactive intermediate between the computer system and its human operator. Man-machine interface improvements for interactive computer software have made dramatic changes to their look and feel--making the user interface more "friendly" and intuitive. Users now expect software user interfaces that are familiar and consistent with their everyday experience in a specialized application domain, like 3-D anthropometry.

The user interface facilitates interactive computer program or system operation by mapping the functionality of the underlying hardware, software and data into commands that the operator can elicit in a meaningful sequence. If operations are repetitious and may become tedious, they should be combined into an integrated new function--often using a macro or learning capability.

User interfaces are highly significant in practice, since a computer system only has utility if an operator can employ it effectively to achieve a desired result or complete a given task.

In the future, as computing becomes even more central to many functions, especially in demanding graphically oriented environments like 3-D anthropometry, the user interface will play an increasingly significant role in a project's success. In this chapter, the key issues in user interface design and implementation are discussed as they relate to 3-D anthropometry.

BACKGROUND

Visual programming and operating environments are commonplace in software development. Most programmers use these environments because of the enhanced productivity, faster debugging and responsiveness inherent in modern software development systems. Examples include the CASE or Computer Aided Software Engineering tools that offer 4th generation programming languages, object oriented programming in standardized procedure oriented languages like C++, data flow language/programming environments and many others. These recently developed tools have eclipsed the more traditional editors, compilers and debuggers that were ubiquitous only a few years ago.

Interactive windowing systems are the de facto presentation of computer operating systems today. For example, it is difficult to find a DOS-based personal computer today. Microsoft Windows has the overwhelming majority of the pc-clone microcomputer market, and it will soon be difficult to imagine a personal computer without a windows-based user interface management system.

This revolution was begun in 1984 with the introduction of the Apple Macintosh, now the archetypical windowing system for desktop microcomputing. In addition to the Macintosh OS and Microsoft Windows, IBM introduced OS/2 for personal computers with lesser success. These trends continue the migration of "workstation" software, originally widely available only on Sun or similar more costly desktop computers to Intel and Motorola processors. The de facto standard in the client-server and workstation world today is X-windows which replaced SunView and others about 3 years ago. The most consistent trends that can be identified is the improvement in computational capability associated with single chip processors and rapid migration toward open systems, especially UNIX-based.

Principles of user interface design for man-machine systems and usability have been the subject of many recent studies. Nielsen and Levy (1994) reported a metaanalysis of computer usability preference and performance. The usability of computers has been increased by tailored user interface design for specific application domains. In this chapter we introduce the technology of user interfaces and

identify issues germane to 3-D anthropometry software systems.
In application specific design, there is need to identify domain expertise at the earliest stages to assure that the ultimate system is responsive to requirements that are unfamiliar or unknown to the developer. Imposed solutions seldom work in complex applications. The user interface must be tailored to the specific needs dictated by the application, and not vice versa.

The implementation can be achieved in practical terms only by use of an appropriate user interface management system (UIMS). Several are available and some of these offer cross platform development capability so one user interface specification will operate seamlessly on Macintosh, PC/Windows and X-Windows for workstations.

Several software systems have been developed specifically for anthropometry applications. These include: CrewChief, Mannequin, Combiman, Jack™ and many others. Each of these systems includes a user interface and produces hard and softcopy display output. The strengths and weaknesses of each system's user interface are illustrated in this chapter.

Practical software development in visual object oriented programming environments allows rapid prototyping of interactive point and click user interfaces that incorporate predefined elements associated with the environment. High productivity can be achieved by programmers using these development environments which result in reusable software that is portable across platforms and adheres to relevant standards.

INTERACTIVE DEVICES AND ENVIRONMENTS

Interactive devices allow user pointing and event initiation. These include microswitches incorporated into pointing devices such as the electronic mouse (optical or mechanical versions), trackball, joystick, control dials and button or function switches. Typically these devices operate in conjunction with a cursor that is guided on a display screen in real time by the pointer. Graphical and text based window displays are available and may be operated simultaneously.

Windows may be tiled or overlapping. They may be fixed, resizeable and modifiable or not. The number of possibilities is so large that standards have been recommended by several manufacturers, especially Apple for the Macintosh™, to maintain a higher degree of consistency among application programs and allow users to carry basic knowledge of file system and text editor operation between applications. There is little need for the user to learn multiple alternatives to accomplish the same end.

It is now often the case that any single operation may be performed on the same system by different avenues. These can be initiated by macro, menu pick, command key or icon click. The large number of alternatives empowers the user to operate the software by any route known to them.

Programs are different in an interactive environment. From initiation to termination, interactive programs are guided in their execution sequence by the user, rather than rote sequence of commands. Innumerable alternative sequences may be possible, and user events dictate the specific order according to decisions made by the user based upon the presentation of information in the midst of the program's operation that are displayed on a crt screen.

User interface software development has advanced quickly since the introduction of windowing at Xerox PARC. A new vernacular and terminology has emerged, with many abstract concepts being adopted and incorporated in familiar software products such as Microsoft Word and Excel, Word Perfect, Lotus 1-2-3, and many others.

The importance of these developments to 3-D anthropometry is a reflection of the central role that interactive graphics plays in modern technology. A user with access to a suitable workstation and CD-ROM data disk will be able to accomplish more than an entire laboratory and suite of computers, provided that the software system available to the user has appropriate functionality, the data set is

complete and germane to the user's needs, and the user interface is well designed and efficient.

A much greater burden is now placed on the software system designer to anticipate and provide functionality and a means to access it in newly developed software. For reasons of cost effectiveness, cross platform development, portability and reusability of software is mandatory. Fewer people must accomplish more with the computer systems in less time and produce a superior product. This can only be done by taking full advantage of software development aids, especially object oriented programming environments and an integrated user interface management system.

The graphical user interface (GUI) has become a dominant software development activity. Development tools for multimedia user interface are now available, allowing the inclusion of sound, and video, as well as a wide variety of fonts, colors, and patterns. A GUI is the now-familiar collection of icons and buttons that users see on their screen and click on to launch programs. GUIs first replaced text menus when Apple Computer introduced its Macintosh platform, and are now standard in the Microsoft Windows environment also.

OBJECTS

Object technology (and computer technology in general, for that matter) depends heavily on the concept of the hierarchy. Developing object-oriented software means building hierarchies. It means grouping like things together--dogs with dogs, cats with cats--grouping groups, grouping groups of groups, etc. Talent in object-oriented software design and development involves the ability to recognize and create consistent patterns among groups.

In the animal kingdom, a dog is real, but higher levels in the classification scheme are abstract. One of the key things about object-oriented technology is that it follows the same idea. It starts with a real object (a document, an inventory list, a video clip, a scanned photograph) and builds around it a hierarchy that enables efficient computer processing.

That is in marked contrast to traditional, procedural ways of thinking about software. In the past, you neither started out nor ended up with something that directly corresponded to anything in the real world. The thinking in the first decades of symbolic computer programming was a computer-centric view of the world. By contrast, the modern thinking is to model the real world; that is, to represent it directly.

One thing that makes objects so exciting is the ability to use the hierarchical structure to create variations on a theme. By analogy, the class "dogs" includes Dalmatians, Sheep Dogs, German Shepherds, Scottish Terriers, Poodles, Chihuahuas, Dachshunds, Irish Setters, Bulldogs, and many more.

If you were going to design a new dog, you wouldn't have to go all the way back to hydrogen, oxygen, and carbon. You could start off with the group of characteristics represented by "dog" (e.g., walks on four legs, omnivorous, gives live birth, is domesticated), and customize just those features necessary for your particular dog.

That is how object-oriented software works. Take an object, customize a few features to meet your needs, and that's it. Well, not quite. Things can and do get complicated. But the point is that object-oriented technology starts and ends with the real world. That fact alone gives the software a higher chance for success than would otherwise be the case (Holtzman, 1995).

Object-oriented programming could transcend computer incompatibilities, simplify programming, and ultimately transform the software industry.

Imagine if all cars had nonstandard engines that were built by hand. And imagine that each make of car needed its own special fuel, which had to be hand blended in a laboratory. In such a world, automobiles would probably play a much diminished role: fuel would be prohibitively expensive and hard to find, and the engines would be difficult to repair.

Computer users have come to accept such a bizarre situation as normal. Most software is

still constructed piece by piece by highly trained craftsmen--a costly and inefficient practice reminiscent of the blacksmiths and wood-carvers of past centuries. Software works only on the type of system it was written for and on compatible versions. And as programs are modified and expanded over time, they become so convoluted and complex that making any changes becomes nightmarishly difficult. The irrationality of the software industry becomes clearer by comparing it with the electronics business, where competing manufacturers long ago settled on standard connections and voltage levels, enabling designers to assemble systems using circuitry and equipment from multiple vendors.

Such problems have intensified with the tremendous growth of computing. Networks are linking desktop machines of all types, and users need to tap large databases residing on incompatible mainframes. Giant software packages may run an entire enterprise or even a whole business sector, such as airline reservations or the stock exchanges. And the quickening pace in many businesses requires more frequent programming changes. Yet today's software remains inflexible, and revisions to large programs often introduce subtle, intractable bugs.

Change is in the offing, however. The computer world has been influenced by emergence of "object-oriented" languages, programs, and databases, which provide potential solutions to many of the difficulties that have long plagued both users and developers of computer systems. Object-oriented technology appears to offer, at last, a convenient way to interlink today's jumble of incompatible computers and software. It could also make programs easier to modify. Some advocates also believe that eventually, object technology can make software production a more efficient and manageable process by allowing the use of interchangeable software "parts" analogous to those used in modern manufacturing.

At the heart of object-oriented technology are self-contained software units called "objects." These are chunks of computer code that describe entities ranging from the concrete, such as an automobile part, to the more abstract, such as an airline reservation. Intrinsic to each software object is a description of its behavior--that is, how it will perform a particular task, like arranging data into alphabetically or numerically ordered lists. Because these traits are built into the object-or "encapsulated"-the programmer need specify only that an object perform a particular task.

This encapsulation makes it easier to cloak differences between incompatible computers. Instead of agreeing to make entire software systems compatible, vendors need only settle on a common way of sending messages to objects. It also allows software to be treated in a more modular fashion, with objects being assembled without regard for what is inside them. Modifying object-oriented software does not require alteration of the objects themselves; instead, the programmer can design new objects that "Inherit" attributes from similar existing ones.

Some proponents believe that object-oriented technology will eventually allow ordinary computer users to make their own programs out of pre-made software objects-with little or no programming experience. Just as it requires no electronics expertise to put together a stereo system from off-the-shelf audio components, so too might computer programs be easily assembled and tailored for individual taste. Because programs written with object techniques will be easier to upgrade, users will ultimately get higher quality products.

The road to an object-oriented world does have obstacles. Although an object-oriented system is more flexible and easier to change, it is also more difficult to develop. Because data and the instructions for manipulating it are "hidden" within each object, testing is difficult. And since programmers have been working with objects for only a few years, they have not yet accumulated the vast body of expertise that accompanies conventional programming methods. Partly because of this relative inexperience, some object-oriented programs tend to work more slowly than traditional software.

In many cases, object technology is being added on to existing software, either to help mask incompatibilities or to add a simpler graphic interface. The technology's greatest impact,

however, will occur when whole software systems are built completely with object methods. Even so, many incompatible versions of object-oriented software could emerge, undermining the technology's promise of becoming a kind of computer Esperanto. Unless standards are established, therefore, the power of objects will not be fully realized.

The potential benefits of object-oriented software appear to outweigh these drawbacks, and so hardware and software makers are wasting no time in developing object-oriented products. IBM designed its highly successful line of mid-sized business computers, the AS/400 series to run with object-oriented code. Hewlett-Packard's New Wave software uses object-oriented techniques to allow PC users to link separate applications programs, even ones that reside on different systems. Borland International, a Santa Cruz, Calif., supplier of database programs for personal computers, now uses object-oriented techniques to write most of its software.

Microsoft offers object-oriented features in the current (1995) version of the Windows operating system for IBM-compatible PCs. Thanks to the object-oriented software, says Microsoft chairman William Gates, it will be easy for programmers to add enhancements to a piece of software without modifying the main program. Gates says that Windows 3.1 makes it possible, for example, to add spoken comments to particular cells in a spreadsheet. And in perhaps the most dramatic development, object technology will be the foundation of IBM and Apple Computer's efforts to link their presently incompatible personal computer systems.

Object Oriented Programming

Object-oriented programming promises to bring some order to a chaotic software scene. Some 100 billion lines of computer code are in use today in the United States, according to estimates cited by management consulting firm Ernst & Young. These programs were developed over the past few decades at a cost of some $2.3 trillion and cost an additional $30 billion a year to maintain. Many massive software systems with hundreds of thousands of lines of code were well documented initially, but after hundreds of modifications and numerous personnel changeovers, it becomes difficult to fathom exactly how the program works, let alone make revisions and add new functions.

The appeal of object-oriented technology stems partly from the weaknesses of conventional software, in both its underlying structure and the methods that have evolved to develop it. Typically, system requirements are formulated and then analysts break the solution into a set of program modules. Skilled specialists tediously code, line by line, each module-a process reminiscent of pre-Industrial Revolution manufacturing. There's little reuse of previously coded subroutines that may perform similar functions, so, in effect, programmers are frequently reinventing the wheel. As work progresses, requirements may be altered and flaws may become apparent in the way the overall programming job has been divided up--but it is extremely difficult to go back and restructure modules once coding is well underway.

In conventional software, each program is built from "procedures," or sequences of coded instructions. Typically, individual programmers or groups of programmers write separate modules, which then work together to perform the task the software is designed for. Each procedure within a module is instructed to operate on certain "data types" (such as calendar dates, dollars, or numbers with fixed or floating decimal points). If a new data type is introduced, a programmer must find and modify all the procedures that deal with it - a difficult and time-consuming task in a large software system with many loops and jumps.

Object-oriented software avoids these problems by combining in each object the programming procedures that define how an entity will behave as well as all the data related to that entity. Procedures, in object parlance, are called "methods." A typical software object might be a simulation of a vehicle; the object's methods would determine, for example, how the car would start, turn, and stop. Objects communicate with each other via specially structured messages. A message, in an object-oriented program, might consist simply of the name of an object followed by the name of the method-for example, "car stop."

One powerful attribute of object-oriented software is that each object has built within it the knowledge for how to respond to a particular message. This allows the same message to be sent to many objects. A software "car" object, for example, would respond to a message of "turn left" much differently than would a software "motorcycle" object. Built into the simulated motorcycle would be the knowledge that a left turn requires leaning.

Probably the most important distinction of object-oriented software is the ability of objects to "Inherit" behavior. Lower-level objects can incorporate the properties of more generic, higher-level objects. Thus programmers can devise hierarchies of objects, each assuming the traits of the object at the higher level. Construction of a "jet airplane" software object, for example, could begin by simply inheriting all the traits of an already defined "aircraft" object and then modifying it. Similarly, a "supersonic fighter" object would automatically assume all the characteristics of a "jet airplane." With conventional software, programmers must copy code-bugs and all-and then modify it. With objects, programmers copy the results of code. It's the difference between photocopying a document and abstracting its main idea.

Inheritance makes software easier to modify. To construct a computer model of a plastic-bodied car, for example, an auto designer would need only change a generic "body parts" object from steel to plastic and write new code to represent the material's different characteristics. The particular body-component objects, such as the "fender" object and the "door" object, would inherit these altered properties without additional reprogramming. In another example, a new airline could be added, with a minimum of fuss, to an object-oriented database program for managing airline reservations. The objects representing the new carrier would simply inherit the general format of price structures and schedules that had been previously defined for a generic "airline" object. The programmer would then have to reconcile only whatever minor differences there might be between the new airline and this generic object. With a conventional database, by contrast, such tasks would force the programmer to start from scratch, says Thomas M. Arwood, chairman of Object Design, a Burlington, Mass., company specializing in object-oriented software.

Microsoft's comprehensive object strategy is built around the open standard of Object Linking and Embedding (OLE) object model and is designed to provide developers with a consistent and open standard for defining what an object is and how objects interact with one another. Microsoft offers independent software vendors and customers an open, standard way to realize all the benefits of component-based software development. For example, users will be able to plug different OLE Custom Controls into a database or spreadsheet application to provide a range of custom functions such as specialized financial modules, equation editing, scientific analysis, run-time tutorials and charting. In the past, the primary benefits of object-oriented programming were directed at programmers; OLE brings the benefits of object technology to a broader audience, including end users, developers and system integrators. OLE is Microsoft's strategic component object model. OLE is not new. It's no secret in the industry that OLE is Microsoft's stated future direction. In the recent past, Microsoft has sponsored conferences and seminars that have focused, in part or in total, on what OLE is, why it's important, and how to work with it now and in the future.

Microsoft is not the only company endorsing and promoting OLE as an industry standard for component-based software development. There were over 150 non-Microsoft OLE-compliant applications shipping by Spring COMDEX 1994. 25,000 copies of Kraig Brockschmidt's book, "Inside OLE 2.0" have been sold, and there are 8,000 developers currently doing OLE development work. (Microsoft Corporation, 1996).

Object Oriented Viewpoint

The movement toward object-oriented software appears likely to be an evolutionary migration. The first generation of such software, exemplified by Hewlett-Packard's New Wave, will mainly help users to interlink existing applications programs.

The second generation of object-oriented software will allow people at many different

locations and using a variety of computer types to work collaboratively. The object-oriented approach greatly aids such teamwork, allowing, say, geographically dispersed design engineers, manufacturing managers, and accountants to collaborate on bringing a new product to market. Such groups typically work on different computers running incompatible software. Object-oriented technology will help transcend these differences. Software developers will be able to devise "smart" applications that will, for example, automatically update all the participants' files based on pertinent results from the work of others.

Eventually, computer users as well as programmers will be able to customize and enhance their programs by selecting from libraries of well-tested software objects. A user of an investment-portfolio management program, for example, could add different types of rules to reflect changes in personal financial needs or in the general economic climate.

The fastest changeover to object-oriented technology is occurring in the software that engineers use to automate the design of complex electronic and mechanical systems. Traditionally, in computer-aided design, each engineer uses a set of specific software-based tools. Object-oriented frameworks will allow engineers to put together a suite of tools from different vendors. The object-oriented software will make it practical for each of these design tools to share a common graphical interface, making them easier to learn and to use. As designers work for hours on their section of an overall project, the object-oriented database will help keep tabs on any changes that might affect other sections. Moreover, object-oriented databases take some of the tedium out of designing. An electronics engineer, for example, could simply specify what task a circuit should perform; the object-oriented database will help translate this specification into a circuit design.

The changeover in business data processing will come more slowly, Atwood says, because present relational databases are well-suited to the file structures common to business applications. Object technology will be used instead to integrate the computer's underlying operations. IBM's AS/400, for example, uses the object approach to provide a simple graphic interface so that it can be run by relatively unskilled operators, even clerks, according to Roy A. Bauer, a quality manager at IBM's Application Business Systems division in Rochester, Minn. Previous mid-sized computers have required specially trained personnel to run, Bauer says.

Another benefit for object-oriented systems is more compact code: he says his company's database management system contains some 250,000 lines of code programmed in an object-oriented language called C++. Three times that much code would be needed, he says, to write a comparable program in C, a conventional programming language that is used in about 80 percent of today's design-automation programming. The shift to an object-oriented model can also greatly reduce execution time-perhaps by three orders of magnitude, according to studies done by Sun Microsystems.

Object Management Group (OMG)

Although touted as a means of overcoming computer incompatibility, object-oriented technology has the potential to exacerbate rather than solve the problem. The proliferation of software development efforts based on object-oriented technology is reminiscent of what has happened with UNIX, a family of operating systems used widely in science and engineering. As it gained popularity, UNIX spawned dozens of conflicting variations that only now are being folded into a standard system.

The potential for object-oriented technology to degenerate into yet another software Tower of Babel led to the formation in 1989 of the Object Management Group (OMG) in Framingham, Mass. More than 150 organizations have joined this standards-setting group, including such industry leaders as Microsoft, Apple, and IBM as well as Japanese and European companies.

OMG hopes to prevent the fledgling object-oriented software marketplace from following the familiar computer industry trajectory. The group intends to forge a consensus on standards for functions common to many types of software, such as exchanging objects over networks and gaining access to remote databases. OMG hopes to convince vendors that without such

standardization, they will have a much more difficult time selling whatever object-oriented products they develop.

Critical to the success of this strategy is devising a standard way for objects to send and receive messages. The goal, explains OMG president Christopher M. Stone, is for objects to interact with each other regardless of how they were originally programmed. This interaction-which should be transparent to computer users-would permit sending electronic mail messages, extracting data for a chart, or swapping information with a distant collaborator using a different computer and software.

To achieve such smooth transactions, OMG's first priority is to establish a standard "object request broker," or ORB, which will act as a sort of traffic cop for interchanges across diverse networks and equipment. Getting the industry to agree to such standards is not easy, however. Already, two groups-one led by Hewlett-Packard and Sun Microsystems and the other by Digital Equipment Corp.- had to be pressed to merge different ORB proposals into a single submission.

Perhaps the most serious drawback to object-oriented software is cost. Some experts contend that it now can cost four or five times as much to design an object-oriented software system as a conventional one. This discrepancy should diminish as a commercial object-oriented market takes shape and programmers build complex software systems by lacing together reusable pieces of code, using powerful development tools now coming on the market.

SOFTWARE RE-USE

By drastically simplifying the production of software, object-oriented technology could turn the software industry upside down. Ultimately, software could evolve into a commodity business, with users and programmers alike shopping for interchangeable software modules.

A leading proponent of this transformation is Brad J. Cox, president of Information Age Consulting in Washington, Conn. Cox points out that the costs of computer hardware have been declining rapidly while there have been only minor improvements in software costs. He sees the object-oriented approach as a way to turn software into a more rational industry, exhibiting the usual learning-curve cost reductions. Objects, he maintains, will turn software into a "manufacturing" business.

Cox uses the analogy of the rise of interchangeable parts in gun making to describe his vision for software evolution. In Revolutionary days, muskets were crafted individually by gunsmiths who embedded their names into each creation. Then, in 1798, Eli Whitney, the Connecticut inventor famous for his cotton gin, contracted with the government to build 4,000 muskets using interchangeable parts. Eight years late, Whitney delivered the muskets to the government and even then they weren't made from truly interchangeable parts. Indeed, not until 50 years later could guns be conveniently assembled; to make the process work, manufacturers had to develop inspection gauges to separate acceptable from unacceptable pieces.

Analogous developments are necessary, Cox maintains, to transform the software industry. Computer programs should be assembled out of pre-manufactured, interchangeable parts. What's also needed is the software analog of a pocket micrometer to assure that each manufactured programming object meets specifications within tolerances: Is the program fast enough? Does it do all the tasks expected of it, quickly enough? Does it consume an acceptably small amount of computer memory?

Cox envisions a software industry structured much differently than today's. Users would pick and choose software objects from a large network of vendors and assemble the objects into a system that meets their precise needs. Cox likens this to the electronics industry, where manufacturers buy integrated circuits (ICs) as commodities and then connect them in different and customized ways. He foresees an emerging market in "software ICs." Standards would ensure that objects sold by different companies would work together.

Other object-oriented specialists laud Cox's vision but stress that it is a long way from realization. "Cox is a little optimistic," says Richard Soley, vice-president and technical

director of OMG. "Not everybody is going to be a tinkerer." Others, such as Adele Goldberg of ParcPlace Systems, which markets tools and generic objects for object-oriented programming languages, believe that market economics dictate against the software-IC approach. Selling small chunks of code to individual users who could assemble them into specialized programs would require a much too elaborate distribution system. Instead, Goldberg suggests, marketing tools and generic objects will serve developers of more general-purpose software packages.

Still, few would argue with the need to turn the software development process into a more efficient activity with more predictable results. Just as the automobile owes its low price and near ubiquity to mass production, so computer software will require a new method of production if it is to fulfill its promise as a source of universally available, easy-to-use information tools. After all, although there is still a place for handcrafted Rolls Royces, it was the mass-produced Model T that changed the world (Haavind, 1992).

OPERATING SYSTEMS

What is the difference between" system software" and "application software"? Where do utilities fit? Are there definite boundaries separating the three categories? Does it matter whether there are boundaries at all, and if so, where they are drawn? Is the definition of an operating system a technical one? Is it legal? Is it market-driven? Is it constant, or does it vary over ?

Consult the typical computer reference or textbooks, and you'll see operating system defined pretty much as follows: "The software responsible for controlling the allocation and usage of hardware resources such as memory, central processing unit (CPU) time, disk space, and peripheral devices. The operating system is the foundation on which applications, such as word-processing and spreadsheet programs, are built. Popular operating systems include MS-DOS, the Macintosh operating system, OS/2, Windows, Windows NT, and Unix." (Microsoft Corporation, 1994).

Most operating system definitions include hardware resource management. But few cover the necessary and sufficient kinds of resource management required for software to qualify as an operating system. At the other end of the scale, if you heap more and more software--particularly programs that clearly are applications--onto the core operating system, what becomes of the definition? Does it need to change? Or does a new product category--OS++ --need to be defined?

This might all seem academic, except that the company that published the definition given above has products spanning both the operating-system and applications categories. Over the years, Microsoft has continually evolved and expanded its working definition of the operating system to the point that the computer business as a whole has been affected. Ask utility vendors what they think about the inclusion of 386/486 memory-management and file-undeletion tools in recent versions of MS-DOS. Ask network and electronic mail vendors what they think about the inclusion of peer-to-peer networking and E-mail clients in recent versions of Windows.

Some organizations demand that Microsoft be split in half--operating systems and applications. To which side would the 386 memory-management group go? The E-mail group? The file-undelete group? What about the Windows "applet" group (responsible for Write, Note-pad, and Terminal)? What about games?

In the definition given earlier, Windows is cited as an example of an operating system. Windows is sold with a popular version of Solitaire; Windows for Workgroups comes with a version of Hearts. Surely games do not help manage system resources--quite the opposite. In fact, their purpose is to expend system resources. What about programming tools? DOS includes DEBUG and QBASIC, which while not state-of-the-art, are certainly capable programming tools.

Suppose you limit the definition to system-resource management software with no user interface. Doing so would, for example, cut MS-DOS down to just two files: IO.SYS and MSDOS.SYS, that together occupy less than 100K of disk space. Doing so would further eliminate COMMAND.COM; the market would

then be dependent on third-party offerings such as JPSoft's 4DOS. (Actually, I like that idea. DOS is light-years better than COMMAND.COM.) The Unix world has had alternate "shells" for years; why not here in the PC world as well?

In the Windows 3.x world, the limited definition would eliminate all but three Windows executable files, plus some support DLL's. Gone would be Program Manager and File Manager, along with all the mini applications. That might not be such a bad thing either.

On the other hand, including Xcopy and Find and DelTree and all the rest as part of the operating system helps ensure a consistent level of quality and consistency, at least among the core file- and disk-management utilities. Or does it? When was the last time you used DOS's Recover command?

DOS = OS + Utilities

The trend seems to be that the operating system will push higher and higher, further and further away from the hardware. It will be more encompassing in the resources it manages, and it will include more and more in the way of utilities, "applets," and adequate if not full-blown applications.

For example, look at what has happened in the evolution from MS-DOS 3.3 to MS-DOS 6.2. Software utilities were not included in DOS 3.3 but are available in MS-DOS 6.2, and every one of those items was originally conceived and sold by a third-party vendor. Most of them are but shadows of their former selves, and some are no longer even with us. Even the biggest utilities vendors (e.g., Symantec/Norton and Central Point) are totally revamping their strategies and product lines.

Microsoft's definition cited both MS-DOS and Windows as examples of operating systems. When you come down to it, MS-DOS manages disk, some peripherals (via a Frankenstein-like kludge of device drivers and TSRs), and memory at a very low level. Almost no programs written to run under MS-DOS use DOS to manage video display or serial communications. Windows picks up where MS-DOS leaves off. Together, the two comprise the resource-manager for Intel-based PCs. Together, they include lots of software, utilities, mini-apps, and applications, formerly considered external to the operating system.

OS/2 ratchets the concept a notch higher, as it includes three operating systems (MS-DOS, Windows, and OS/2). And Windows 95, though it won't support OS/2, also supports three operating systems, and will likely include even more in the way of utility programs. Outside of the DOS/Intel world, the same kinds of things are happening. New object-oriented operating systems like NextStep and Taligent exhibit the same trend, to an even greater degree.

Growth and expansion is not limited to operating systems. Look at the tools market. A compiler, a linker, and possibly a debugger used to define a programming tool. Now CD-ROM-based programming environments come with fancy screen designers, text and bitmap editors, and huge libraries of precanned routines. Third-party software libraries include complete mini-apps--spreadsheets, word processors, database front ends, communications modules, and more. Suchstandard applications as word processors occupy 15 megabytes or more of disk space, and they are supplied with all sorts of fancy tools for document design and layout. Application suites (CD-based, of course) are blowing away "single"function applications.

USER INTERFACE MANAGEMENT SYSTEMS (UIMS)

A giant step up from toolkits are user interface management systems (UIMS). A UIMS gives you a toolkit and a programming environment for using it. With the better systems, the environment is largely visual, so instead of writing C or Pascal code that specifies the numerical coordinates of each button in a dialog box (i.e., 140,29,170,80 for its corners), you can just drag a button out of your design palette and drop it on the screen where it looks good.

Some UIMS packages are limited environments that provide very fast development of simple programs or early prototypes. Others may require more work to

get started, but they allow you to start with a prototype and iterate it into a full- fledged, highly functional application. A survey in 1991 showed that over 40 percent of programmers in commercial environments were using some sort of UIMS with more power than a toolkit, spending roughly 40 percent of their application development time on the code that went into their applications' user interfaces. Toolkit users, by comparison, spent 60 percent of their time on the interface. In both cases, the interface accounted for about half of the total application code (Meyers & Rosson, 1992). The savings can be even greater if you can design your application as an embedded system that uses functionality provided by other programs the user already owns, a technique we'll describe in the section on Microsoft Windows.

The UIMS approach does more than save programming time. It also helps you build a better interface, by maintaining consistency within the application and across applications under a common operating system, and by making it easier to rapidly iterate through the implement-and-test cycle. An additional advantage is that a UIMS can provide answers to the difficult question of what you can legally copy. The fundamental purpose of a UIMS is to help programmers develop interfaces rapidly, by copying controls that users already know. That goal is shared by programmers, users, and the vendor of the underlying operating system. The UIMS is sold by a company that has legal rights to the interface techniques you want to use, and purchasing the UIMS gives you clearly defined rights to sell the systems you develop.

OBJECT-ORIENTED PROGRAMMING (OOP)

Object-oriented programming is a technique for making programs easier to write, easier to maintain, and more robust. The OBJECTS of object-oriented programming are blocks of code, not necessarily on-screen objects, although the on-screen objects usually are implemented with program objects. The program objects have several important characteristics: They are defined hierarchically, with each object being an INSTANCE of a CLASS of similar objects. (A class is also defined in a single block of code.) For example, the blocks of code describing the File menu and the Edit menu would be two instances of the class of menus, and that class could itself be a SUBCLASS of the class of labels. Objects INHERIT the behavior and characteristics defined higher in the hierarchy, unless that inheritance is specifically overridden by the object's code. Inheritance would allow the programmer to change the font of all the menu objects by making a single change to the class definition. Each object also has PRIVATE DATA that defines its own characteristics and maintains information about its current state. Objects communicate with each other by sending MESSAGES. An object's response to a message is part of the behavior that the object inherits or can override.

Object-oriented programming requires an object-oriented programming language, such as C++ or CLOS, that supports the object features in addition to the basic functionality provided by most modern languages. There are differences between object-oriented languages, and not all of them support all of the features described in the previous paragraph. But they do all provide a programming structure that's an excellent match to the needs of user-interface programming. If you need another menu, you just create another instance of the menu class -- a single line of code. Then you fill in the details unique to that menu: what are the names of the menu items, where is it located on the screen, and what messages should each item send when it is selected. Additional code objects implement the functions of the program: sorting, searching, whatever. These code objects, sometimes called HANDLERS, are invoked by messages sent from menu items and other user controls, as well as from other code objects. If you need to modify the program's behavior, the class hierarchies let you make sweeping changes consistently and easily, while the private data allows you to change the behavior of an individual object without fear of unexpected side-effects.

EVENT-DRIVEN PROGRAMS

The traditional paradigm for computer programs is sequential: the user starts the program and the program takes control, prompting the user for input as needed. It's possible to write a highly interactive program (for example, a word processor) using the sequential programming paradigm, but it isn't easy. The resulting programs are often very modal: an input mode, an edit mode, a print mode, etc. The programmer has to anticipate every sequence of actions the user might want to take, and modes restrict those sequences to a manageable set.

For a simpler and more natural approach, modern interactive systems use an event-driven paradigm. Events are messages the user, or the system, sends to the program. A keystroke is an event. So is a mouse-click. Incoming e-mail or an empty paper tray on the printer might cause the system to generate an event. The core of every event-driven program is a simple loop, which waits for an event to take place, responds appropriately to that event, and waits for another. For example, the event loop of a word processor would notice a keystroke event, display the character on the screen, and then wait for another event. If it noticed a mouse-double- click event, it would select the word the mouse was pointing at. If it noticed a mouse-click in a menu, it would take whatever action the menu item specified. Early interactive systems actually required the programmer to write the event loop, but in a modern UIMS environment the programmer just needs to build objects (menus, windows, code, etc.) and specify how they send or respond to messages.

RESOURCES

Resources, for our purposes, are interface-specific information such as menu titles or button positions, which are stored so they can be easily changed without affecting the underlying program functionality. (A system may also treat the main program code as a resource.)

On some systems you might change the resources by editing values in a text file; on others you might need to use a special resource editor. But it typically won't require recompiling the application itself, and it won't require access to the source code. During prototyping, a few simple changes to resources might dramatically improve an interface, with no "real" programming. When the system is ready to ship, resources can be changed so the product can be used in countries with a different language.

INTERAPPLICATION COMMUNICATION

Interapplication communication describes a situation in which two programs, running at the same time, exchange data. For example, a word processing program might send some numbers to a spreadsheet, which could calculate their average and send it back to the word processor. That would allow the word processor to have the calculating power of the spreadsheet, without duplicating the code. Communication between applications is a common technique on minicomputers (the world of UNIX), but it's only recently been implemented in personal computer operating systems. That's partly because early personal computers could only run one application at a time, and partly because, unlike the command-driven software that forms the basis of most minicomputer applications, interactive graphical systems can't easily be adapted to respond to commands from other programs.

Two major personal computer software environments, Microsoft Windows (currently version 3) and Apple's Macintosh System (version 7), support interapplication communication. They provide a communications pathway between applications, and they specify standard data formats for the interaction. As we write this, Windows seems to have the lead both in functionality and number of third-party applications that another application can access. On either the Mac or Windows, you should look for places where interapplication communications can help you avoid rebuilding systems that the user already has and knows (Lewis & Rieman, 1994).

The Windows programming model is event-driven and graphic object oriented. In other

words, programming in Windows involves creating objects and modifying aspects (or properties) of those objects based on different events. Consider the following sample program that presents two buttons to the user. If the user chooses the Count button, the program counts the records in the database and displays the result in a window. The user can press the Exit button to exit from the program.

The Windows interface is one that has been regarded throughout the industry as being very user-friendly. Familiar objects such as push buttons, radio buttons, list boxes, and a wide variety of colors and screen fonts are generally more appealing than standard ASCII text characters.

You do not have to worry too much about different devices such as monitors, printer drivers, and so on. The Windows operating environment takes care of most device compatibility and user preference issues. In addition, because Windows handles and processes events, you will find it much easier to create and manage many aspects of an application.

3-D ANTHROPOMETRY REQUIREMENTS

A software system for 3-D anthropometry implies high quality interactive color graphics intensive operations that are performed with an intuitive user interface via multiple pointing and interactive devices in parallel operation. This user interface must be familiar and consistent with other applications on the same computer workstation, and with the application domain. Iconic or faithful body surface renderings that can be interactively controlled by the user are central to this issue.

The 3-D anthropometry software system should be portable and reusable in whole or in part for emerging and future applications without the need for reimplementation of infrastructure modules. This should be done using modern methods of object oriented programming in a "standardized" programming language, such as C++.

The graphically oriented user interface should be highly interactive and easy to use. A self documenting implementation that is oriented to the needs of casual and naive' user's is indicated in 3-D anthropometry. Not only must the system be fast and responsive, but a robust implementation is needed.

Adherence to extant standards for UIMS and networking implies that the implementation of 3-D anthropometry software is compliant with the needs of "open systems". Both cost of development and time available for implementation must be minimal. The software operates in a networked and internetworked environment without the need for specialized applications and systems personnel who have specific expertise in the relevant network standards.

This chapter is concerned with the software for post-processing of data that has already been collected, archived and indexed into an available data base. Issues of data acquisition systems for 3-D anthropometry are not specifically addressed.

PLATFORM-INDEPENDENT GRAPHICAL USER INTERFACE (PIGUI)

A Platform-Independent Graphical User Interface (PIGUI) toolkit is a software library used by a programmer to produce GUI code for multiple computer systems. The toolkit presents functions and/or objects (along with a programming approach) independent of the specific GUI. For our purposes, a PIGUI must support the native look-and-feel for GUIs under at least two different operating systems (so just supporting OpenLook and Motif on two Unix boxes doesn't count). The toolkit does not necessarily provide any additional portability features.

Consider a programmer who decides to build a program that will operate on many different computer types. A PIGUI toolkit is used to handle the GUI portion of their code. With a PIGUI toolkit the toolkit's "PIGUI_menu" function is invoked. When the code is compiled with the "Macintosh" flag set, the PIGUI library

puts a Mac menu on the screen in response to the PIGUI_menu call. When code is compiled with the "Motif" flag set, the call causes the library to display a Motif-style menu. All this happens (theoretically) without having to change the source code. If you are careful to make non-GUI code portable, you can have a single program (with a single source) that works on multiple platforms.

There are a few things to consider before deciding whether to use a PIGUI. First, most (and maybe 'all' depending on whom you believe) of the PIGUIs will slow the execution of your code. The feature set is limited to that provided by the PIGUI unless you add code outside the toolkit (but, then again, why use the PIGUI in the first place if you're going to code around it?). Bugs in any toolset (PIGUI or otherwise) filter down to your production code. Fewer people know how to code any specific PIGUI than do a platform-specific GUI (e.g., MS-Windows), so wizardly help will be limited. The PIGUI only deals with the GUI aspects of your program -- you're on your own for other portability issues. Finally, if the vendor goes out of business you may be out-of-luck for support of future OS enhancements (source code can ease, but not eliminate, the pain of a vendor closing its doors).

Language Choice

Many C programmers will look at the purchase of a PIGUI library as a great opportunity to migrate to C++. If the library takes full advantage of C++, the programmer will have to use C++ methodologies (not just a C++ compiler with C syntax) to use it. When one ports a C program to such a library, one should expect to invest a 'significant' amount of effort learning about (and modifying his code to take advantage of) classes, inheritance, and constructors in order to complete the port. Of course, if one wants his C code to become C++ code, this is a necessary exercise anyway.

IEEE PIGUI Standard

IEEE P1201.1 is a draft standard for multi-GUI APIs, an API that would be implementable on top of a wide range of GUI bases. The API must be independent of the look and feel of the delivered interface, yet must support a wide range of interface functionality.

This group has focused its work on developing a programming language independent model of GUI programming, on which language specific bindings will be based. The model abstracts core elements of the computational model of several existing multi-GUI toolkits expressed in an object-based computational model. The objects defined in the standard do not correspond to the specific programming elements of any one GUI, but can be mapped onto the programming elements of any of the target GUIs. Several participants plan to sketch language bindings for several different languages, including C, C++, and Ada.

USER-INTERFACE APPROACHES

Most, if not all, of the available GUI programming products take one of three approaches to providing platform independence. The two most common approaches are the "layered" and the "emulated" user interface but an up-and-coming approach is "API emulated" interface.

Products using a layered interface access native, third party, GUI-building toolkits to provide the look-and-feel compliance for each particular GUI. Layered user interfaces have the advantage that, since they depend on other products which concentrate on a single GUI, they have to provide less software (and, hence, are usually less expensive) than emulated interfaces. Layered interfaces are also more likely to get the native look-and-feel correct on all platforms. Most PIGUI products fit in this category.

In an emulated user interface, the PIGUI's resultant code produces low-level calls and all the look-and-feel compliance is handled by the PIGUI software itself (e.g., for OpenWindows support, the software would *NOT* produce an XView program that must be compiled with the XView toolkit; the software would produce code that interfaces directly with X intrinsics). To provide an emulated user interface, a vendor has to develop a lot of extra code for look-and-feel support. Emulated user interfaces have the

advantage that someone on a Motif workstation, for example, can see how the Macintosh-style UI will look (since the look-and-feel is part of the product). Emulated interfaces have the opportunity to provide a faster GUI than does a layered interface; in addition, it does not require you to purchase (or learn how to use) other kits to build GUI software.

A third approach to platform independence is emulating one of the supported target's APIs (usually, the Microsoft Windows API) to target other GUIs. With one of these products, one would program using the emulated API and the code would be (to the extent to which that the product provides portability) portable to other GUIs.

FEATURES AND SUPPORTED PLATFORMS

The currently available GUI programming products are similar in their basic functionality; they each provide function calls or classes that allow the user to build windows, buttons (regular as well as radio buttons and check boxes), menus, menu bars, and the like. Areas of contention include:

- availability and price of source code,
- printer support,
- support for international character sets,
- capability to support draw-package-like features,
- bitmap (and icon) support,
- whether the product has a WYSIWYG GUI builder (most do),
- the choice of implementation language, and
- the approach to platform independence.

The following abbreviations are commonly used for GUI software systems:

App	AppWare, Novell
Aspect	Aspect, Open Inc.
Views	C++/Views, Liant
CLIM	Common Lisp Interface Manager, several vendors
CommonV	Glockenspiel CommonView, Computer Associates
DCLAP	Don's Class Application library, Don Gilbert
Galaxy	Galaxy, Visix
Guild	Guild, Guild
JAM	JAM, JYACC.
libWxm	libWxm, Visual Solutions
MAINWin	MAINWin/Cross-Development Kit, MAINSoft Corporation
Menuet	Menuet/CPP, Autumn Hill Software, Inc.
MEWEL	MEWEL UIL, Magma Systems
ObViews	ObjectViews C++, Quest Windows Corporation
OI	Open Interface, Neuron Data
Opus	Opus, WNDX
OpenUI	OpenUI, Open Software Associates
PSM	Presentation Services Manager, Lancorp Pty Ltd.
ScrMach	Screen Machine, Objective Interface Systems, Inc.
StarVie	StarView, StarDivision
SUIT	Simple User Interface Toolkit, University of Virginia
VisWork	VisualWorks, ParcPlace
Wind/U	Wind/U, Bristol Technology
wxWind	wxWindows, Artificial Intelligence Applications Institute
XVT	XVT Portability Toolkit, XVT Software Inc.
zApp	zApp, Inmark
Zinc	Zinc, Zinc

Table 6-1: PLATFORM VS. PRICE (US$ except where noted)

Vendor	ASCII	DOS	Win(s)	Win/NT	OS/2	Motif	Open-Look	Mac	PenOS	Next-Step
App(d)	.	soon	yes	soon	soon	yes	-	yes	-	.
Aspect	yes	yes	1495	.	.	2495	yes	1495	.	.
Views	-	soon	749	soon	995	1999	-	yes	.	.
CLIM	.	.	.	.	.	yes	yes	soon	.	.
CommonV	.	.	yes	.	yes	yes	soon	soon	.	.
DCLAP	.	.	(k)	.	.	(k)	.	(k)	.	.
Galaxy	-	-	7800	soon	9600	(m)	(m)	9600	-	.
Guild	-	-	895	895	895	soon	-	895	-	.
JAM	yes	yes	yes	.	.	yes	yes	.	.	.
libWxm	-	-	(h)	(h)	(v)	yes	-	(v)	-	.
MAINWin	-	-	(h)	(h)	(v)	5000n	-	(v)	-	.
Menuet	-	499	599	-	599	999	-	.	yes	.
MEWEL	1595	395u	(h)	(h)	795	-	-	(v)	-	.
ObViews	-	-	yes	yes	.	yes	-	yes	-	.
OI	yes	yes	5800	6850	6850	9850	9850	4800	.	.
Opus	.	695	695	yes	yes	695	695	695	.	.
OpenUI	yes	-	3500	soon	4900	7900g	-	3500	(w)	.
PSM	.	.	yes	.	.	yes	.	soon	.	.
ScrMach	495	495	1995	soon	-	(p)	-	-	-	-
StarVie	-	-	499	soon	495	soon	soon	soon	.	.
SUIT	.	(k)	(k)	.	.	(k)	(k)	(k)	.	.
VisWork	.	.	2995	.	2995	4995	4995	2995	.	.
Wind/U	-	-	(h)	(h)	(v)	9950	-	(v)	-	.
wxWind	soon	-	free	soon	-	free	free	-	-	.
XVT(c)	call	1450	1950	6300ab	1950	6300a	6300	1950	.	.
zApp	-	495	495	495	695	soon	-	soon	-	.
Zinc(e)	1499e	299e	299(f)	299(f)	299e	1499	-	299ej	299	.
Vendor	ASCII	DOS	Win(s)	Win/NT	OS/2	Motif	Open-Look	Mac	PenOS	Next-Step

(a) This is the price for platforms other than x86-based computers. For x86-based machines (under DOS/UNIX/Xenix -- where applicable), the price is $1950.

(b) For non-x86 platforms, check for availability -- Alpha and MIPS supported.

(c) Interactive design tool is $1200 extra ($2900 for non x86-based X-windows). The design tool is not available for the C++ product.

(d) Novell're currently determining pricing information -- they use the term 'negotiated'.

(e) Zinc requires a single-time purchase of the Zinc GUI engine. This is $499. After this price, the individual GUIs to be supported are added-on.

(f) Win16, Win32s, and Win32 are packaged together.

(g) for a PC-based Unix, we're talking $5850.

(h) This product uses the MS Windows API; so, in that sense, it supports MS Windows.

(j) Pre-release.

(k) This product is free for non-commercial use. If you make a profit, you'll have to check with the vendor for pricing and availability.

(m) The price is per machine. For $9600, you get Motif, OpenLook, CUA, and Microsoft Windows on a single machine.

(n) The cost drops for subsequent copies. Number 2 is $3500 and number 3 is $2000.

(p) The pricing here is a little complicated. It was explained to me as follows. "We have both systems based pricing and floating license pricing. The system based pricing runs from $3K (small Sun or SCO) to $24K (big VAX or Sun 2000). The Unix Motif floating license pricing is $6K for the first license and $3K for each additional license."

(s) That's Microsoft Windows (TM).

(u) Price does not include source code (the other MEWEL products do).

(v) Microsoft Wings (scheduled to ship in the first half of 1994) can be used to port Windows API to Macintosh System 7. Micrografx's Mirrors can be used to port Windows source to OS/2.

(w) Does work on PenOS systems, but does not *yet* have Pen extensions.

(x) That's OpenLook.

(y) That's NextStep.

There are two groups of products. The lower-priced group is usually C++, is a more recent introduction to the market, is almost always a layered GUI, and concentrates on PC-based operating systems. Products from the higher-priced group usually offer a more stable platform with both greater breadth and depth than does the previous group. In either case, the cost premium for UNIX support is usually a factor of 3 -- that is, the GUI package for a UNIX platform for any PIGUI product is usually 3 times as expensive as the version for DOS/MS-Windows. Other "personal" operating systems (e.g. OS/2 and the Mac) vary as to whether they follow the UNIX pricing or the PC pricing. These are merely observations, your mileage may vary.

Table 6-2: FEATURES

Vendor	Type(p)	Eval(a)	Source	Royalty	Language	Builder(g)
AppWare	.	.	.	no	.	(m)
Aspect	.	30	(e)	no	C	yes
Views	layered	(c)	free	no	C++	yes
CLIM	.	(u)	.	.	Cmn Lisp	(u)
CommonV	layered	.	yes	no	C++	.
DCLAP	.	free	free	.	C/C++	.
Galaxy	emulate	(d)	(e)	no	C/C++	yes
Guild	.	.	(f)	no	C	yes
JAM	layered	.	yes	no	C	yes
libWxm	API emu	.	.	.	.	.
MAINWin	API emu	30	no	(w)	C/C++	$199
Menuet	.	.	.	.	.	.
MEWEL	API emu	.	(r)	no	C(s)	(t)
ObViews	layered	.	.	no	C++	.
OI	emulate	(x)	.	no	C/C++	yes
Opus	emulate	.	.	no	.	.
OpenUI	layered	(q)	(e,b)	no	C(h)	yes
PSM	.	.	.	yes	.	no
ScrMach	layered	30	(e)	no	Ada	free
StarVie	layered	30	yes	no	C++	yes
SUIT	.	free	free	.	C	.
VisWork	emulate	(c)	100000	yes	SmalTalk	yes
Wind/U	API emu	(v)	(f)	no	C/C++	(t)
wxWind	.	-	free	no	C++	(n)
XVT	layered	(y)	yes	no	C/C++	yes
zApp	layered	60	free	no	C++	$499
Zinc	layered	60	free	no	C++	yes
Vendor	Type(p)	Eval(a)	Source	Royalty	Language	Builder(g)

(a) This is the number of days that the product can be evaluated. Inside this time, the software can be returned for full money back.

(b) Open Software Associates is willing to make a deal for source on a case-by-case basis.

(c) They offer a 30 day 'test drive' evaluation. This costs $50 (applicable toward cost of product).

(d) Give them a P.O. They'll give it back if you don't like the product. Not sure what the pricing is. They also require a 1 week, $2500 course they require you to take to get an evaluation.

(e) Source code is held in an escrow account. You can't get to it unless the company goes belly-up. This helps you protect your investment -- if the company goes belly-up, you can do the software maintenance yourself.

(f) You can buy it, or you can get an escrow account.

(g) This is a WYSIWYG GUI Builder.

(h) Pascal, Cobol, and Ada are supported, too, but there wasn't room.

(m) They've reconfigured AppMaker (for the Mac) and AppStudio (MS Windows) to be GUI builders.

(n) Uses SunOS's DevGuide.

(p) Type means 'emulated', 'layered', or 'API emulated'. This describes how the product approaches support for various GUIs.

(q) They charge (about $500) for a 90 day (money applicable to purchase) evaluation period. Included is a 1-day training course and phone and fax support.

(r) ASCII and OS/2 versions come with source for free. The DOS version is an additional $400 with source.

(s) You can program in the MS Windows API or use MFC, OWL, or C++/Views.

(t) Any MS Windows Application Builder will work.

(u) Different LISP vendors support CLIM -- each provides a different set of options and pricing structures.

(v) A 30 day evaluation costs $250.

(w) MAINWin kind-of charges royalties. Every machine on which an application developed with MAINWin is to be run needs the a license for the shared libraries. The cost runs between $195 (quantity 1) and $156 (quantity 100) per machine.

(x) These guys have a 'flexible evaluation structure'.

(y) About $125 to evaluate the thing -- this includes a full set of documentation.

The following table makes the most sense for operating systems that work on various types of hardware (e.g., UNIX, Windows NT) rather than for OSs dedicated to a certain type of hardware (e.g., DOS, Microsoft Windows, Macintosh).

A \`y' indicates that support has been verified by a user report.
A \`c' indicates that the hardware/OS is claimed to work in vendor literature.
An \`e' indicates that this is the API emulated by the software.
A \`b' indicates that the hardware/OS is in beta.
A \`p' indicates that the hardware/OS is planned, but not yet in beta.
A \`.' indicates that whether this combination works is unknown.
A \`-' indicates that the vendor doesn't support that hardware.
A \`*' points you at footnote info.

Table 6-3: HARDWARE VENDORS SUPPORTED

AppWare	Aspect	Views	CLIM	CommonV	DCLAP	Galaxy	Guild	JAM	Libwxm	Menuet	MAINWin	MEWEL	ObView	OpenInt	OpenUI	PSM	ScrMach	StarVie	SUIT	VisWork	WNDX	Wind/U	wxWind	XVT	zApp	Zinc	Systems
p	c	-	.	.	.	-	.	.	.	.	-	c	-	.	-	.	-	-	c	.	.	.	-	.	c	y	DOS Graphics
-	c	p	.	.	.	-	.	.	.	.	-	c	-	.	-	.	c	-	.	.	c	.	-	.	c	c	DOS Text
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	-	.	c	.	.	.	.	.	.	.	y	c	16-bit DOS Extender
.	.	.	.	.	.	.	.	.	.	c	.	c	.	.	-	.	c	.	.	.	.	.	.	.	-	c	32-bit DOS Extender
-	c	-	.	.	.	-	.	.	.	.	-	c	-	.	y	.	c	-	.	.	.	.	p	y	.	c	ASCII Text
c	c	y	.	c	c	y	c	.	e	c	e	e	c	c	y	c	c	c	c	c	c	e	c	c	c	y	MS-Windows 3.x Win16
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	c	MS-Windows Win32s
c	c	b	.	b	c	c	c	.	.	.	-	-	c	c	y	b	-	c	c	c	c	.	-	c	b	b	Macintosh
.	.	.	.	.	.	.	.	.	.	.	-	.	.	.	p	.	-	b	.	.	.	.	.	.	.	p	Macintosh PowerPC
p	.	c	.	c	.	c	c	.	.	c	-	c	-	c	y	c	-	c	.	c	b	.	-	c	c	c	OS/2
p	.	p	.	.	.	y	c	.	.	.	c	p	c	c	b	.	p	c	.	.	.	.	b	c	c	c	80x86 / Windows NT Win32
p	.	p	.	.	.	b	.	.	.	.	c	p	.	c	-	.	p	c	.	.	.	.	-	c	.	p	DEC AXP / Windows NT
p	.	-	.	.	.	b	.	.	.	.	c	p	.	.	-	.	p	p	.	.	.	.	-	c	.	.	MIPS / Windows NT
-	c	-	.	b	.	y	.	.	.	.	-	-	.	c	-	.	-	c	c	c	c	.	c	c	.	-	SunOS / OpenLook
c	c	c	.	.	c	y	b	.	c	.	c	-	.	.	c	.	c	c	c	.	.	y	c	c	y	c	SunOS / Motif
.	.	b	.	.	.	.	.	.	.	.	c	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	Sun Solaris 2.x / Motif
p	c	-	.	.	.	.	.	.	.	.	p	-	.	.	c	.	c	-	.	.	.	.	c	y	.	.	ISC / Motif
.	.	.	.	.	.	.	.	.	.	.	.	-	.	.	.	.	.	.	.	.	.	c	.	c	.	.	DEC AXP OSF1 / Motif
.	.	.	.	.	.	.	.	.	.	.	.	-	.	.	.	.	.	.	.	.	.	.	.	c	.	.	DEC AXP OpenVMS / Motif
c	.	-	.	.	.	y	.	.	.	.	p	-	.	c	c	.	c	p	.	c	.	.	c	c	.	.	DEC Ultrix / Motif
p	c	p	.	.	.	y	.	.	.	.	p	-	.	c	c	.	c	p	.	.	.	p	.	c	.	p	DEC Vax VMS
.	.	.	.	.	.	.	.	.	.	.	.	-	.	.	.	.	.	.	.	.	.	.	.	c	.	.	AT&T System 3000/ Motif
p	c	c	.	.	.	.	.	.	.	.	p	-	.	c	c	c	c	p	.	.	.	.	c	c	y	c	SCO Unix/Xenix / Motif
p	c	-	.	.	.	c	.	.	c	.	p	-	.	c	-	.	-	p	.	.	.	p	c	c	.	.	MIPS / Motif
.	.	.	.	.	.	.	.	.	.	.	.	-	.	.	.	.	.	.	.	.	.	c	.	c	.	.	HP 700/800 HPUX / Motif
c	c	c	.	.	.	y	.	.	c	.	c	-	.	c	c	.	c	p	c	c	.	.	c	c	y	c	HP 9000/HPUX / Motif
p	c	p	.	.	.	y	.	.	c	.	c	-	.	c	c	.	c	c	c	c	.	y	c	c	y	c	IBM RS-6000/AIX / Motif
p	c	-	.	.	.	c	.	.	c	.	c	-	.	c	-	.	c	p	c	.	.	y	y	c	c	c	Silicon Graphics
-	.	-	.	.	.	.	.	.	.	.	-	-	.	.	-	c	-	-	.	.	.	.	.	.	.	.	Pyramid

Table 6-4: SUPPORT FEATURES

Vendor	With sale	800 number?	BBS?	Compuserv?	FTP server?	Read USENET?	Other	Support contracts
AppWare	yes	soon	no	yes	yes	yes	(b)	TBD
Aspect	?	?	.	.	.	.	.	$200-$800/yr
Views	60d	no	yes	no	no	yes	.	$250-$500/yr
CLIM	(c)	(c)	(c)	(c)	(c)	(c)	(c)	(c)
CommonV	(a)	?	.	.	.	.	.	-
DCLAP	none	no	no	no	yes	yes	.	-
Galaxy	none	yes	no	no	yes	yes	(k)	$1,995/yr
Guild	90d	?	.	.	.	.	.	$100/month
JAM	.	?	.	.	.	.	.	.
libWxm	.	?	.	.	.	.	.	.
MAINWin	1 year	yes	.	.	yes	.	(h)	$1000/yr(e)
Menuet	.	?	.	.	.	.	.	.
MEWEL	yes	no	yes	yes	yes	yes	.	$250/yr
ObViews	.	?	.	.	..	.	.	yes
OI	.	?	yes	.	.	yes	.	$1200-$2400/yr
Opus	.	?	.	.	.	.	.	-
OpenUI	90d	no	soon	no	soon	yes	(h)	12%-30%/yr
PSM	.	?	.	.	.	.	.	-
ScrMach	1 year	yes	no	no	no	yes	(hk)	20%/yr
StarVie	.	yes	yes	yes	no	yes	.	-
SUIT	.	no	.	.	yes	.	(d)	-
VisWork	(f)	yes	yes	yes	(g)	.	.	$675/yr
Wind/U	.	no	no	no	yes	yes	(mn)	12%-20%/yr
wxWind	.	no	no	no	.	yes	.	-
XVT	1 year	yes	yes	yes	yes	.	.	(call)
zApp	forever	no	yes	yes	no	yes	.	-
Zinc	forever	no	yes	yes	yes	yes	.	$499/yr(j)
Vendor	With sale	800 number?	BBS?	Compuserv?	FTP server?	Read USENET?	Other	Support contracts

(a) CommonView provides free maintenance for MS-Windows and OS/2. 15% of cost is required for Motif, however.

(b) There's a mailing list (appware-info-request@serius.uchicago.edu for more info).

(c) CLIM is a multi-vendor product. See the individual vendor for information.

(d) There is a SUIT mailing list. E-mail 'suit-users-request@uvacs.cs.Virginia.EDU' for mor information.

(e) That's for one person. The second person is $700, and subsequent users are at $500.

(f) Installation and temporary evaluation help plus one free general support question.

(g) Gopher service.

(h) Support (including distribution) by e-mail.

(j) This is for their higher-end support. Simple support still comes for free.

(k) They support an email mailing list.

(m) WWW support.

(n) Newsletter.

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CHAPTER VII: STANDARDS RELEVANT TO 3-D SURFACE ANTHROPOMETRY

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INTRODUCTION

As discussed earlier in Chapter II, measuring the human form is a practice dating back many centuries. Anthropometry measuring practices, techniques, and methodologies have evolved over time into a scientific field employing state-of-the-art technologies. As with all fields of science, experience has shown that certain methodologies are well suited for specific applications. This has resulted in the adoption of standard practices and methodologies for anthropometric measurement and data collection activities. Many of these adopted methodologies have been incorporated into formal standards or handbooks as a guide for practicing professionals. Chapter VII will explore the existing anthropometry standards currently in force. The list of standards provided cover applications in both the commercial and military realm.

The latter half of Chapter VII will address the growing issue concerning visualization data standards. The use of digital technology to measure, visualize, and analyze 3-D anthropometric objects coupled with the move to integrate all 3-D anthropometric data into a distributed information system has generated the need to standardize the collection and manipulation of data. The issues of visualization data standards deal primarily with the compatibility of digital data between multiple users and systems. Factors that have a significant impact on data compatibility include the formatting, displaying, storage, interrogation, communication, and reduction of data. This chapter will examine these issues and provides one possible approach to standardizing 3-D anthropometric data.

ANTHROPOMETRY RELATED STANDARDS

The anthropometry standards section provides a brief overview of the documents that are currently used throughout the anthropometry community as guidelines for collecting and analyzing anthropometric survey data and for developing anthropometric design requirements. Anthropometry is a diverse field consisting of numerous disciplines with each discipline having its own set of unique standards. In addition, each country may also have their own unique set of standards relative to each discipline. The intent of this section is to provide a listing of some of the more common standards, relative to the criteria identified above, that describe how anthropometry is performed today. The list is not comprehensive and will undoubtedly overlook some standards used by readers of this report. However, the list should provide the reader a representative sample of the types of standards available. The documents discussed in this section include industry and military standards, handbooks, technical reports, and advisory publications. These documents are referred to as "standards" in a general sense throughout the remainder of the chapter even though some of the documents may not fit the exact definition of a standard. These documents are included since they serve the same function as standards by providing overall guidance and high level direction in their respective subject areas.

The standards discussed in this chapter are divided into two major categories. Standards relative to anthropometry surveys, measurements, and data analysis are included in the anthropometry data collection and analysis category. Standards relative to the design of

human systems or the human-system interface comprise the anthropometric design category. Within each category, the standards are organized into groups of multi-national or country-specific standards.

The standards contained under the multi-national grouping include both multi-national military and industrial standards. Examples of multi-national military organizations are the Air Standardization Coordinating Committee (ASCC) and the North Atlantic Treaty Organization (NATO). The countries who are member nations of these military organizations participate in International Military Standardization programs for the purpose of minimizing the logistical, technical, procedural, and operational obstacles encountered during a war or emergency situation. The International Standards Organization (ISO) is the prominent multi-national organization in developing industrial related standards. Countries who adopt ISO standards seek to take advantage of the economy realized in combining their efforts and resources.

The second class of standards includes those standards that are country specific or do not fall under the umbrella of a multi-national adopted standard. These standards are included in this report as they provide insight into significant areas of anthropometric related work. Due to the large number of these standards, a description of each standard is not provided. However, the general content of the standard can be easily identified from the publication title.

To facilitate the accuracy of the standard descriptions, the descriptions were taken directly from the document summaries with minor revisions as needed to ensure clarification of the standard's objectives and use.

Anthropometry Data Collection and Analysis Standards

Data collection and analysis refers to activities related to designing an anthropometric survey, recording the survey data, and the subsequent analysis of the collected data. Specific areas of interest include the choice of anthropometric variables to be measured in the survey, the optimal measurement techniques, and the analysis of the measured data. The following publications address these general areas to one extent or another.

Multi-National Standards

Military Standards

• *ASCC Advisory Publication 61/37*
Anthropometric Limitations for the Selection of Aircrew and for Aircraft Crew Stations in the ASCC Nations

Document Type: Advisory Publication
Preparation Activity: Air Standardization Coordinating Committee

ASCC 61/37 provides technical data on the individual ASCC nation's anthropometric selection criteria for aircrew personnel. The standard includes the tabulation of the differences in national selection criteria and the identification of anthropometric limitations for individual aircraft crew stations. The objectives of this standard are twofold: 1) to facilitate the comparative study of anthropometric limitations applied to the selection of aircrew across member nations, and 2) to facilitate the selection of aircrew for exchange between member nations and ensure that the body dimensions of selected aircrew personnel do not exceed local aircraft specific anthropometric limits.

• *ASCC 61/38*
The Smoothing of Percentiles: An Empirical Evaluation of Several Methods

Document Type: Advisory Publication
Preparation Activity: Air Standardization Coordinating Committee

ASCC 61/38 catalogues the results of an evaluation effort to compare various computational procedures for smoothing the lower and upper percentile distributions of anthropometric data sets. Twelve methods of computing percentiles (11 which provide a smoothing of the results) were studied. The basic methodologies used were: 1) Gram-Charlier Functions, 2) Frequency-Table Method, 3) Smoothed-Frequency-Table Percentiles, and

4) Regression Methods. The evaluation indicated that all procedures provided reasonable results, especially if the body size measurement data were not too badly skewed.

• *ASCC Advisory Publication 61/105/9*
Application Oriented Selection of Anthropometric Dimensions

Document Type: Advisory Publication
Preparation Activity: Air Standardization Coordinating Committee

ASCC 61/105/9 provides a list of the more common and useful variables to be included in anthropometric surveys. A list of useful variables are provided for different applications which included the areas of general data, cockpit geometry, and personal equipment. The objective of this standard is to assist investigators in the selection of some useful and commonly taken variables for a given application.

• *ASCC Advisory Publication 61/105/11*
A Basis for Common Practices and Goals in the Conduct of Anthropometric Surveys

Document Type: Advisory Publication
Preparation Activity: Air Standardization Coordinating Committee

ASCC 61/105/11 provides guidance in the follow areas of Anthropometry: 1) the definition of base sets of anthropometric variables, 2) the location and method of identification of standard anatomical landmarks, 3) the method of achieving standardized subject postures, 4) the presentation of generalized, non-equipment specific, definitions for the base sets of anthropometric variables, and 5) recommended units of measurement and accuracy required for measuring equipment. The objective of this standard is to present data which will assist ASCC member countries in pursuing common practices and goals in the planning and conduct of anthropometric surveys and to provide a common basis for comparing the anthropometric data of member countries.

• *STANAG 2177*
Methodology for Anthropometric Data

Document Type: NATO Standardisation Agreement
Preparation Activity: North Atlantic Treaty Organization Standardization Program

STANAG 2177 provides a set of standardized methods for measuring the head, body, hands, and feet. This NATO standard is to be used in all anthropometric surveys and during the implementation of *STANAG 2335, Interchangeability of Combat Clothing Sizes*. The objective of this standard is to ensure more accurate comparisons of anthropometric data between participating NATO member nations.

• *STANAG 2335*
Interchangeability of Combat Clothing Sizes

Document Type: NATO Standardisation Agreement
Preparation Activity: North Atlantic Treaty Organization Standardization Program

STANAG 2335 establishes a sizing system in combat clothing between NATO member forces. The purpose of establishing this standard is to facilitate interchangeability of combat clothing sizes between NATO forces. Body measurements are used as the basis for comparison and interchangeability.

Industry/Commercial Standards: Size Designation of Clothes

The following ISO Standards deal with the size designation of clothes for a variety of male and female age groups and types of clothing. These standards form a series of standards that establish a system of designating clothing sizes that prescribe both the control dimensions on which the size designation system is based and the method of indicating the size designation on the clothing's label. These standards are used in conjunction with *ISO 3635, Size Designation of Clothes - Definitions and Body Measurement Procedure*, and *ISO/TR 10652, Standard Sizing System for Clothes*. *ISO 3635* defines body dimensions and specifies a standard procedure for measuring the human body. *ISO/TR 10652* is a type 2 technical report that establishes a body sizing system to be used for compiling

standard garment sizes for infants, men and boys, and women and girls.

• *ISO/TR 10652*
Standard Sizing Systems for Clothes

• *ISO 3635*
Size Designation of Clothes - Definition and Body Measurement Procedure

• *ISO 3636*
Size Designation of Clothes - Men's and Boy's Outerwear Garments

• *ISO 3637*
Size Designation of Clothes - Women's and Girls' Outerwear Garments

• *ISO 3638*
Size Designation for Clothes - Infant's Garments

• *ISO 4415*
Size Designation of Clothes - Men's and Boy's Underwear, Nightwear, and Shirts

• *ISO 4416*
Size Designation of Clothes - Women's and Girl's Underwear, Nightwear, Foundation Garments, and Shirts

• *ISO 4417*
Size Designation of Clothes - Headwear

• *ISO 4418*
Size Designation of Clothes - Gloves

• *ISO 5971*
Size Designation of Clothes - Pantyhose

• *ISO 7070*
Size Designation of Clothes - Hosiery

• *ISO 9407*
Shoe Sizes - Mondopoint System of Sizing and Marking

Industry/Commercial Standards: Anthropometric Measurement

• *ISO/DIS 7250*
Basic List of Anthropometric Measurements

Document Type: ISO
Preparation Activity: International Organization for Standardization

ISO/DIS 7250 is currently pending publication release.

• *ISO 8559*
Garment Construction and Anthropometric Surveys - Body Dimensions

Document Type: ISO Standard
Preparation Activity: International Organization for Standardization

ISO 8559 defines the location of body dimensions taken on anthropometric surveys and for the preparation of garment patterns and garment stands, and specifies a standard procedure for measuring the body. This standard is typically used as a reference document that provides the definitions for and the location of body dimensions used in garment construction.

Country-Specific Standards

• *AL/CF Technical Report (unpublished)*
Fit Testing Handbook

Document Type: Technical Report
Preparation Activity: Armstrong Laboratory, U.S. Air Force

• *ASTM D4910*
Standard Tables of Body Measurements for Infants, Ages 0 to 18 Months

Document Type: ASTM Standard
Preparation Activity: American Society for Testing and Materials

• *ASTM D5219 Rev B*
Standard Terminology Relating to Body Dimensions for Apparel Sizing

• *ASTM D5585*
Standard Table of Body Measurements for Adult Female Misses Figure Type, Sizes 2-20

• *ASTM D5586*
Standard Tables of Body Measurements for Women Aged 55 and Older (All Figure Types)

• *BSI BS 1887*

1966 Person Weighing Machines and Height-Measuring Equipment for Hospitals, Welfare and Health Services

Document Type: British Standard
Preparation Activity: British Standards Institute

- *BSI BS 3666*
1982 Size Designation of Women's Wear

- *BSI BS 6185*
Size Designation of Men's Wear

- *BSI 7231: Part 1*
1990 Body Measurements of Boys and Girls from Birth up to 16.9 Years Part 1: Recommendations of Body Dimensions for Children

- *BSI 7231: Part 2*
1990 Body Measurements of Boys and Girls from Birth up to 16.9 Years Part 2: Recommendations of Body Dimensions for Children

- *BSI PP 7310*
1990 Anthropometrics An Introduction

- *CAN/CGSB 49.6-M85*
Canada Standard System for Sizing Girls' and Boys' Apparel

Document Type: Canadian Standard
Preparation Activity: Canadian General Standards Board

- *CAN/CGSB 49.6-M78*
Application of the Canada Standard System for the Sizing of Girl's and Boys' Apparel (Amendment 1 Nov 1983)

- *CAN/CGSB 49.7-M78*
Canada Standard System for Sizing Infants' Apparel; (Amendment 2 Apr 1985) (Supplement No.1 June 1991)

- *CAN/CGSB 49.8-M89*
Girls' and Boys' Canada Standard Sizes Model Forms, Regular Range - Dimensions

- *CAN/CGSB 49.9-M89*
Infants' Canada Standard Sizes Model Forms - Dimensions

- *CAN/CGSB 49.201-92*
Canada Standard System for Sizing Women's Apparel

- *CAN/CGSB 49.202-92*
Application of the Canada Standard System for the Sizing of Women's Wearing Apparel

- *CAN/CGSB 49.203-M87*
Canada Standard Sizes for Women's Apparel - Trade Sizes (Supplement No. 1 June 1991)

- *CAN/CGSB 49.204-M89*
Junior, Misses and Women's Canada Standard Sizes Model Forms - Dimensions

- *CAN/CGSB 49.212-M84*
Skirts, Junior, Misses and Women's Sizes - Dimensions

- *CNS L1022*
Glossary of Terms Used for Apparel (Measuring Part) (Jan) (12658)

Document Type: Chinese Standard
Preparation Activity: Chinese National Standards

- *DIN ENGLISH 33402*
Human body Dimensions; Principles of Dimensioning Passages and Accesses

Document Type:
Preparation Activity: Deutsches Institute for Normung E.V.

- *JIS L 0103*
General Rule on Sizing Systems and Designation for Clothes

Document Type: Japanese Standard
Preparation Activity: Japanese Industrial Standards

- *JIS L 0111*
Glossary of Terms Used in Body Measurements for Clothes

- *JIS L 0112*
Glossary of Terms on Parts and Measurement of Clothes

- *JIS L 4001*
Sizing Systems for Infants' Garments

• *JIS L 4002*
Sizing Systems for Boys' Garments

• *JIS L 4003*
Sizing Systems for Girls' Garments

• *JIS L 4004*
Sizing Systems for Men's Garments

• *JIS L 4005*
Sizing Systems for Women's Garments

• *JIS Z 8500*
Ergonomics - Anthropometric and Biomechanic Measurements

• *SAA AS 1344*
Size Coding Scheme for Women's Clothing (Underwear, Outerwear and Foundation Garments)

Document Type: Australian Standard
Preparation Activity: Standards Association of Australia

• *SAA AS 1954*
Size Designation Scheme for Men's Clothing (Including Multiple Fitting Outerwear and Industrial Wear)

• *SBAC RS 186*
Standard Airman

Document Type: SBAC Standard
Preparation Activity: Society of British Aerospace Companies

• *SNZ NZS 8771*
Size Designations and Body Measurements for the Sizing of Ready-To-Wear Clothing for Babies and Infants Aged 3 Months to 5 Years (Reconfirmed 1983).

Document Type: New Zealand Standard
Preparation Activity: Standards New Zealand

• *SNZ NZS 8772*
Size Designations and Body Measurements for the Sizing of Girls' Ready-To-Wear Clothing (Reconfirmed 1983).

• *SNZ NZS 8773*
Size Designations and Body Measurements for the Sizing of Women's Ready-to-Wear Clothing

• *SNZ NZS 8774*
Size Designations and Body Measurements for the Sizing of Boys' Ready-To-Wear Clothing (Reconfirmed 1983).

• *SNZ NZS 8775*
Size Designations and Body Measurements for the Sizing of Men's Ready-to-Wear Clothing Other Than Shirts

Anthropometry Design Standards

Evolving work in the design of human systems and the human-machine interface has resulted in several standards to assist engineers in the design of human systems. The following list of standards highlights the prevailing material available to human system design engineers. Since Anthropometry is the focus of this report, the standards provided below have been selected due to their relevancy to anthropometric design requirements.

<u>Multi-National Standards</u>

Military Standards

• *STANAG 3705*
Human Engineering Design Criteria for Controls and Displays in Aircrew Stations

Document Type: NATO Standardisation Agreement
Preparation Activity: North Atlantic Treaty Organization Standardization Program

STANAG 3705 is used in conjunction with *STANAG 3994* for the design and layout of cockpit controls and displays. STANAG 3705 is included in this group of anthropometry related reports since it addresses operator workspace and reach requirements.

• *STANAG 3994*
Application of Human Engineering to Advanced Aircrew Systems

Document Type: NATO Standardisation Agreement
Preparation Activity: North Atlantic Treaty Organization Standardization Program

STANAG 3994 is a general level standard for applying human engineering considerations in the design, development, and evaluation of advanced aircrew systems. Requirements for operator workspace and reach design considerations are addressed.

• *NASA-STD-3000*
Man-Systems Integration Standards

Document Type: NASA Standard
Preparation Activity: National Aeronautics and Space Administration

This NASA standard is applicable to all manned space programs including NASA, military, and commercial programs. The standard is divided into five volumes. Volume I - Man-Systems Integration Standards contains design considerations, design requirements, and example design solutions for the development of manned space systems. Volume II contains the appendices for the material in Volume I. Volume III is a condensed field guide of pertinent quantitative data extracted from Volume I. Volume IV - Space Station Man-Systems Integration Standards has the same scope as Volume I but specifically oriented to the Space Station. Volume V documents all the man-systems integration design requirements for the development of man-tended payloads to be serviced by the Space Transportation System (STS) Orbiter Vehicle. This standard includes an Anthropometry section that examines the design requirements for human personal equipment and workstation relative to a microgravity environment.

Industry/Commercial Standards

• *CEN PREN 979*
Basic List of Definitions of Human Body Dimensions for Technical Design

Document Type: European Anthropometric Standard
Preparation Activity: European Committee for Standardization

Country-Specific Standards

• *AFSC Design Handbook 1-3*
Human Factors Engineering

Document Type: AFSC Handbook
Preparation Activity: U.S. Air Force Systems Command

• *ANSI 101*
Personnel Protection - Men's Limited-Use and Disposable Protective Coveralls - Size and Labeling Requirements

Document Type: ANSI Standard
Preparation Activity: American National Standards Institute

• *ASTM F1166*
Standard Practice for Human Engineering Design for Marine Systems, Equipment and Facilities

Document Type: DoD Adopted Industry Standard
Preparation Activity: American Society for Testing and Materials

• *ASTM F1337*
Standard Practice for Human Engineering Program Requirements for Ships and Marine Systems, Equipment, and Facilities

• *DOD-HDBK-743*
Anthropometry of US Military Personnel

Document Type: DoD Handbook
Preparation Activity: Department of Defense, U.S.

• *MIL-HDBK-759*
Human Factors Engineering Design for Army Materiel

Document Type: Military Handbook
Preparation Activity: U.S. Army

• *MIL-STD-1472D*
Human Engineering Design Criteria for Military Systems, Equipment and Facilities

Document Type: Military Standard

Preparation Activity: U.S. Army

Application to 3-D Scanning Technology

3-D anthropometry uses state-of-the-art digital technology that has the capability to measure hundreds of thousands of points on the human body with high degrees of accuracy and precision. The application of this technology to the anthropometry field dictates the need to revisit many of the methodologies currently in place relative to anthropometric survey design, data collection, data analysis, and anthropometric related design. Many of the standards relative to these areas may need to be revised when applied in the context of 3-D scanning technologies. As 3-D scanning technologies become more common place, new or revised standards will eventually emerge. One area of 3-D scanning technology where standardization is critical is in the compatibility or standardization of digital data between multiple users and computer systems. The standardization of data for 3-D visualization is the issue addressed in the remaining section of chapter VII.

VISUALIZATION DATA STANDARDS

New technologies and the increasing demand for improved anthropometric designs has made 3-D surface anthropometry a crucial area of present day research in medicine, human biology, manufacturing and the military. Examples of design areas that require improved anthropometric techniques include breast prosthesis (Jones et al., 1989), manufacturing applications using 3-D body data (Jones, West, & Brooke-Wavell, 1993), helmet mounted display systems, and protective garments (Gordon & Friedl, 1994). Further examples of where 3-D surface anthropometry is being applied can also be found in Chapter II.

3-D surface scanning consists of both surface and volumetric scanning. Numerous techniques and technologies are available to perform both types of scanning methods. A description of these technologies is found in Chapters II and III. The wide selection of 3-D scanning technologies has provided researchers and designers with enhanced capabilities that can be tailored to their areas of interest. On the other hand, the proliferation of new technologies has resulted in different hardware platforms, visualization and analysis software, data formats, and data storage structures which makes the sharing of data difficult, if not impossible, between users of different systems. Chapters IV and VI present a sample of the various types of hardware platforms and software systems used in the 3-D surface scanning community. A quick review of these chapters highlights the extent of the incompatibility issues and reinforces the need for data standardization within the anthropometry community.

A prominent factor in the data standardization issue is the wide array of data file formats currently in use within the medical, computer graphics, electronic communications, and computer-aided design/computer-assisted manufacturing fields. A comprehensive listing of these file formats is contained in Chapter V. Given the many applications available, it would not be practical to develop a single universal data file format. However, a common standard among certain application areas could provide the level of standardization needed. The following sections will address this issue and propose one potential data format standard.

Other areas of concern include differences in data reduction techniques, data storage structures, and data communications. A wide variety of data reduction techniques (decimation, compression) are available as well as different data storage structures and data communication protocols. This chapter will also address these issues and propose some potential options.

The success of 3-D anthropometry and its usability for design and fitting are largely dependent on the adoption of standards for digital image display, programming, storage, and communication protocols. Standards are needed for image data obtained from 3-D surface and volumetric scanner systems, as well as data reduction, data formats, and means of data interrogation (Jones, Li, Brook-Wavell, & West, 1994). The adoption of standards will facilitate the interpretability of disparate

components such as anthropometric data, imaging software, and hardware platforms.

Existing Data Formats

Existing data formats which are likely to be relevant to three dimensional (3-D) anthropometry fit into three basic categories: images, graphics, and CAD/CAM.

Firstly, and probably the most basic are plain image formats, such as Graphical Interchange Format (GIF), Joint Picture Experts Group (JPEG), JPEG File Interchange Format (JFIF), and Tagged Image File Format (TIFF). These are only concerned with storing a pixel based view (a raster image) and are not able to contain further details. They also typically lack any internal organization, such as hierarchy of components. However, JPEG format, which is flexible, may have value in storing and transferring raw scanned data because of its capabilities for data compression and transportation on the internet.

Secondly, there are ways of storing more general pictures on computer systems. These range from application programming interfaces and their associated data storage files, such as Programmers Hierarchical Interactive Graphics Structure (PHIGS) and Graphical Kernel System metafile (GKS) through to graphical descriptions which are often called Metafiles. An example would be the Computer Graphics Metafile (CGM). All of these are concerned with storing the elements which go to make up a picture, in terms of shapes, text fonts, etc. These are concerned with storing the display information, rather than the underlying information. For example, this would mean storing a master image which was shown on the display, rather than the data used to created the image. Due to the almost infinite number of different images potentially required in 3-D anthropometry, this approach is unsuitable.

The third category covers mainly Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) and computer Aided Engineering (CAE) applications. Apart from proprietary formats used by all CAD/CAM/CAE systems, there are standards which in principle could be applicable. Examples of this include Initial Graphics Exchange Specification (IGES) and Standard for the Exchange of Product model data (STEP). These formats, although designed with a particular application in mind could perhaps be adapted to the needs of 3-D anthropometry. However, such sophisticated and complex formats would require special software to read and write whenever it was to be used. This would need to be written for every type of computer system used in 3-D anthropometry.

However since many institutions and research groups involved in 3-D anthropometry have relatively unsophisticated systems, such formats are unlikely to be useful. A format which is self-documenting and in a form readable by a human operator is preferred. Such a format would be easily portable between computer systems, and could even be interpreted manually if the necessary software wasn't available.

Existing data formats also rarely allow for more than a fixed set of information to be stored, and it becomes very difficult to add new items. Current research activities are principally concerned with 3-D coordinate measurements. It seems possible that now or in the near future many additional measurements might be made, including body mass; whole body density, density of specific body parts; skin color and reflectivity; skin thickness; elasticity, etc. All of these may be required to be accommodated by the data format.

There is potentially a huge amount of information which could be stored about the human body, and probably a large number of samples will be stored. The data structure used should therefore be as compact as possible, while retaining the above properties.

Proposal for a data format for use in 3-D Anthropometry

The data which are stored depends somewhat upon the anthropometric data which can be collected. An existing system (Jones et. al, 1989) within our HUMAG Research Group, at Loughborough University, is taken as the basis for the following proposal. This "body scanner"

produces a set of co-ordinate data, measuring the surface of the subject. From the 3-D co-ordinate information, many further measurements may be derived by statistical means or using specific algorithms, such as the surface area, volumes, lengths and circumferences of various body parts etc. Rather than store all of these in the same data file, it is proposed to just store a basic representation of the body shell, and to use this to derive all further measurements.

Similarly, the co-ordinate data produced consists of a series of slices taken at fixed intervals in a vertical axis. Body representations may be inferred by taking these slices as the basis for B-spine or polygonal data sets which give a 'smooth' body outline. However, the exact type of representation used may depend upon the application, the individual 'body', or even personal preference. Rather than decide upon a representation, it would be more flexible to store just the co-ordinate points of the slices and to derive the required curves and surfaces as required. While this takes some degree of computation to achieve, it is available on quite modest workstations, and relieves the need for complex curve representations in the data file.

To make the data format easily portable and easy to manipulate it should be written in plain American Standard Code for Information Interchange (ASCII) text. Co-ordinate information can be easily represented by columns of figures. These files could thus be edited manually if necessary using very basic software. Plain text files will be larger than equivalent binary files, but will be easily portable, easy to manipulate with unsophisticated software. There are also compression standards which work very efficiently with text, producing a very high percentage of compression. For example, adaptive Lempel-Ziv coding as used in the UNIX compress command reduces the file size by 50-60%.

Much work in 3-D anthropometry takes place on a particular part of the body, such as the head. A hierarchical data structure could contain sections for each major component of the body, such as head, torso, left arm, right arm, left leg, right leg. Each of these could then have subdivisions, so for instance each leg might be divided into thigh, calf and foot. Further divisions could be used as necessary or appropriate until deemed unnecessary. At this point the data would be stored. It is important to have internationally agreed-upon standards of anatomical/anthropometric terminology for defining body segmentation.

A data file should not need to be complete to be valid. For instance it should be acceptable for a data file to contain only information about the torso and nothing about other body parts. Further information might be added later, or not required for particular applications.

The precise format of the individual data elements, most importantly at this stage the co-ordinate data, will need careful attention, including such details as units, co-ordinate system, origin, etc. No attempt is made here to tackle this problem. The data could then be included to gain a plain text form, perhaps as columns of figures. An illustrative example follows:

```
        Heading
TITLE "3-D Anthropometry Data/Sample 31"
DATE 13 June 1994
UNITS m

END HEADER
BEGIN DATA

BEGIN PART HEAD

END PART HEAD

BEGIN PART TORSO

END PART TORSO

BEGIN PART LEFT_ARM

END PART LEFT_ARM

BEGIN PART RIGHT_ARM

END PART RIGHT_ARM

BEGIN PART LEFT_LEG
        BEGIN SUBPART THIGH
                BEGIN COORD_DATA
                0.000 0.000 0.000
                1.000 0.568 1.267
```

```
            ...
            END COORD_DATA

            BEGIN DENSITY_DATA
            ...
            END DENSITY_DATA
            ...
        END SUBPART THIGH
        BEGIN SUBPART KNEE
        ...
        END SUBPART KNEE
        ...

    END PART LEFT_LEG

    BEGIN PART RIGHT_LEG
    ...
    END PART RIGHT_LEG
```

Data Exchange

Having a standard format for a data file still leaves the need to exchange data files between computer systems. Given the current wide variety of computer systems in use in 3-D anthropometry, this is hard to define in any detail for all possible cases. However, certain suggestions may be made.

Ideally, data file transfers would occur over a Wide Area Network (WAN) such as the Internet. In such circumstances electronic mail would provide the simplest method of transfer for most institutions (where used), although constraints may sometimes exist in terms of the maximum file size which can be transmitted. As an alternative, a standard protocol such as the File Transfer Protocol (FTP) could be used. Both approaches would work for single and multiple files, and achieve rapid transfer. However, not all systems currently have access to the Internet, and so alternatives are required.

One possibility is the use of transportable disks. The most prevalent would be 3.5" IBM-PC compatible high density, 1.44Mbyte floppy disks. These may be used on nearly all modern PCs and Macs and on many UNIX workstations. It might be argued that given the very modest price of a suitable machine, the 3.5" floppy could be assumed as a standard. The basic 3.5" disk can accommodate 1.44 Mbytes of information, which would probably easily hold a single 3-D anthropometry data file. However, in some situations many files would need to be transferred. In such a case, a common piece of software which runs on IBM-PC compatible machines might be used to take a set of files, compress them, and store them on a sequence of floppy disks. The same software could be used at the other end to input the sequence of floppy disks and produce the set of files. One piece of software which can do this is called PKZIP/PKUNZIP by a company called PKWARE Inc. This is widely available at a nominal cost.

Finally, a physical link could be made from one machine to another. This has many drawbacks concerned with compatibility of hardware sockets, cables and software at either end, although in a limited set of circumstances this could be achieved.

In exceptional circumstances, given a plain text (and human readable) data format, this might be printed out, sent to another site, and either scanned using Optical Character Recognition (OCR) software if available or retyped manually. However, the length, and likelihood of errors make this a rather remote possibility.

Conclusions

Some existing data interchange formats, especially those in use in Computer Aided Engineering, may be adaptable to 3-D anthropometry. However, these formats require sophisticated software both to generate them and to extract data from them. This software is unlikely to be generally available. It is therefore recommended that a simple, clear text data interchange format be adopted. This will of course need to be developed in much greater detail than is present in the outline given in this paper.

Physical transfer of data between widely differing computer systems is simplest if those systems are networked. If they are, then simple transfer tools such as FTP are recommended. If networking is not available, then a widely supported transfer medium such as an IBM PC compatible diskette will frequently suffice.

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14. Abstract

This document, in seven chapters, describes the dramatic changes taking place in the field of anthropometry due to advances in 3-D imaging technology. Chapter I explains how 3-D technology can overcome many of the limitations of traditional anthropometry; Chapter II discusses applications for 3-D anthropometry; Chapter III compares traditional and 3-D data collection methods; Chapter IV discusses ways to display 3-D images for users of the data; Chapter V addresses database management issues; Chapter VI explains how the latest user interface design techniques can help users of 3-D data; and Chapter VII examines 3-D data standardization issues and provides a list of current standards for 3-D data.

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